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A Water Quality Model for the South Platte River Basin

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The water quality model PIONEER-I is a steady-state program that simulates the behavior of the following water quality parameters: Total nitrogen; total dissolved solids; zinc; dissolved oxygen; carbonaceous biochemical oxygen demand; fecal coliform bacteria; phosphorus; ammonia; nitrite; nitrate; chlorophyll a. The model was set up on the entire length of the South Platte River from Eleven Mile Canyon Reservoir to its confluence with the North Platte River.

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A WATER QUALITY MODEL FOR THE SOUTH PLATTE RIVER BASIN

DOCUMENTATION REPORT

APRIL 1974

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

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A WATER QUALITY MODEL FOR THE SOUTH PLATTE RIVER BASIN

DOCUMENTATION REPORT

by

William W. Waddel
Charles R. Cole
Robert G. Baca

for the

Office of Research and Monitoring
ENVIRONMENTAL PROTECTION AGENCY

Project #211B01179
Contract #68-01-0702

April 1974

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SUMMARY

The water quality model PIONEER-I is a steady-state program that simulates the behavior of the following water quality parameters:

- Total Nitrogen
- Total Dissolved Solids
- Zinc
- Dissolved Oxygen
- Carbonaceous Biochemical Oxygen Demand
- Fecal Coliform Bacteria
- Phosphorus
- Ammonia
- Nitrite
- Nitrate
- Chlorophyll a

The model was set up on the entire length of the South Platte River from Eleven Mile Canyon Reservoir to its confluence with the North Platte River. In addition, ten major tributaries to the South Platte and a number of smaller streams were modeled.

The model was calibrated using flow and water quality data collected on the river in late summer 1971 and winter 1971-72. The model was successfully calibrated to describe dissolved oxygen-biochemical oxygen demand mechanisms and nutrient distributions.

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SECTION I

CONCLUSIONS

As a result of the studies conducted on modeling of the water quality in the South Platte River Basin the following conclusions can be drawn:

- It is practicable to set up and calibrate a mathematical water quality model which considers numerous interactive constituents on a large and complex river basin such as the South Platte River Basin.

- In the South Platte River Basin concentrations of many important water quality parameters such as dissolved oxygen, biochemical oxygen demand, soluble phosphorus and total dissolved solids can be predicted with reasonable accuracy using the water quality model.

- During certain times of the year the interactions of the various forms of nitrogen in portions of the river basin cannot be accounted for.

- Although water quality data are generally sufficient throughout the river basin to allow for calibration of the model, no data exist for two important phenomena affecting the dissolved oxygen in the waters: algal photosynthesis and respiration and benthic oxygen uptake. In addition river travel times and velocities are not well known throughout the basin.

SECTION II

RECOMMENDATIONS

It is recommended that every effort be made to encourage the use of the water quality model of the South Platte River Basin by regional and local agencies and groups. It is only through this type of repeated and continuous use that the model can be refined and developed into a reliable and trusted tool for managers of water resources.

Two special studies should be conducted to improve the model's predictive capability. First, a study of the nitrogen dynamics occurring below the major municipal sewage treatment plants should be conducted. This study should be specifically designed to determine the behavior and fate of the highly concentrated ammonia nitrogen present just below the treatment plant outfalls. Second, data should be gathered on algal photosynthesis and respiration, benthic oxygen uptake, and river velocities and travel times. These data would improve the dissolved oxygen predictions of the water quality model.

SECTION III

INTRODUCTION

The management of the water resources within a river basin such as the South Platte, where water is scarce and in great demand, is a very complex problem. In the past, standards for the treatment of industrial and municipal wastes which were discharged into rivers and streams were based primarily on public health considerations. When population and industrial densities within the river basin were relatively low, no real problems occurred from the lack of an overall management policy because the water bodies were generally able to assimilate the small amounts of untreated effluents without detrimental effects. However, with the rapid development presently taking place, there is a great need to develop water management policies for the basin.

To assist in the development of these policies, the engineer/planner needs tools for analyzing the effects of alternative plans on the resources so that the various competing uses for the region's water may best be satisfied and the quality of the water maintained. The tools should allow the engineer/planner to easily investigate the effects of various management alternatives, such as (1) advanced waste treatment facilities, (2) regional treatment plants versus many smaller plants, (3) siting of treatment plants, and (4) power, irrigation, industrial development, and recreation.

A necessary first tool in developing this new management system is the ability to quantitatively describe the water quantity and quality parameters and their interactions within the river system. A number of factors complicate the development of such a tool, including (1) basin size, (2) dynamic characteristics of basin water quality and quantity, (3) multiplicity of water uses, (4) poorly defined relationships between water uses and resultant effects, (5) large amounts of data requiring compilation and analysis, and (6) interaction of the multitude of local, state and Federal governmental functions involved.

The use of mathematical modeling techniques to describe parameters of interest represents a logical method of efficiently and economically developing the required management tool. Mathematical modeling is an extremely flexible technique, allowing simplification of the problem statement to any degree necessary for accomplishing the objective. Thus, the model builder can progress even though portions of the problem are at that time known to be ill-defined. These segments of the model can be greatly simplified, while providing for the future development and incorporation of more realistic relationships. While the ability to simplify problems in the model is an advantage, it can also represent a serious limitation. Once a segment of a problem has been simplified, its original meaning or significance can easily be ignored. Therefore, effective formulation and use of the model must be predicated on the user's extensive practical knowledge and experience with the problem under investigation.

Recognizing the need for a comprehensive water-resources management tool for the South Platte River Basin, the EPA requested that a mathematical model be expanded and applied to this river basin. The model is designed for use as a planning tool and not for detailed scientific investigations. Therefore, a precise real-time simulation is impractical because of the large area being considered, crude estimates of future water uses, the resultant effects of such uses, and the limited data base.

In view of the above considerations, the EPA selected the DOSAG-I model as a basis for developing a usable tool for the South Platte River Basin. The model is used for investigating steady-state conditions and appears adequate for its intended use. However, to increase the model's capability, flexibility and ease of application, modifications and expansions were made to include the following important water quality parameters.

CONSERVATIVE PARAMETERS

- Total Nitrogen
- Total Dissolved Solids
- Zinc

NONCONSERVATIVE PARAMETERS

- Dissolved Oxygen
- Carbonaceous Biochemical Oxygen Demand
- Fecal Coliform Bacteria
- Phosphorous
- Ammonia
- Nitrite
- Nitrate
- Chlorophyll a
- General N^{th} Order Decay

The model includes all of the South Platte River from Eleven Mile Canyon Reservoir to its confluence with the North Platte River. In addition, ten of the major tributaries to the South Platte River and ten smaller streams in the basin have been modeled.

This report documents PIONEER-I, a digital computer code developed by Battelle Northwest for application to the South Platte River Basin. The overall solution technique utilized by PIONEER-I, the individual quality models used and the application and operation of the code are described, as well as the calibration and verification studies, including a discussion of the time regimes and methods used in calibration and verification of the model, the sources of data and the problems encountered. Appendices A and B present detailed input instructions, an annotated small test problem, program and subroutine flow diagrams, a program listing and variable descriptions.

SECTION IV

DESCRIPTION OF THE PIONEER-I CODE

PIONEER-I is an expanded version of the DOSAG-I code which was originally developed by the Federal Water Pollution Control Administration and later revised by the Texas Water Development Board.[1] PIONEER-I is computationally similar to DOSAG-I, but has been expanded to predict the following water quality parameters.

- Total nitrogen (conservative)
- Total dissolved solids (conservative)
- Metal ion (conservative)
- Phosphorus (first or second order reaction)
- Fecal coliform bacteria (first order reaction)
- Ammonia (first or second order reaction)
- Nitrite (first or second order reaction)
- Nitrate (first or second order reaction)
- Carbonaceous biochemical oxygen demand (first order reaction)
- Chlorophyll a (coupled with the nutrients in the phosphorus and nitrogen cycles)
- Dissolved oxygen (including benthic demand, carbonaceous BOD, ammonia and nitrite oxidation, and algal photosynthesis and respiration as a function of chlorophyll a concentration)
- General decay model (n^{th} order decay reaction)

The problem is solved in Lagrangian coordinates for a given set of flow conditions, waste source strengths, reach temperatures, quality model reaction constants and water diversion data. The river system is broken down into a number of stretches and the stretches are further divided into reaches. As with DOSAG-I, a reaeration model is chosen for each reach. In addition, regression constants, based on exponential fits of velocity versus flow and depth versus flow, are input for each reach. Mean monthly temperature factors are chosen to simulate other months of the year and flows are specified at headwater locations. The program option which permits the use of flow augmentation to maintain specified minimum DO levels in the river system is carried out by an internal iterative process. Two other options are available, as they were in the original DOSAG model, which allow a series of cases to be run with one input deck. Up to four BOD treatment factors can be specified and the code will perform the

calculations for each factor. The other option allows up to twelve different temperatures and corresponding headwater flows to be specified; the program performs the computations for each set of values.

SOLUTION TECHNIQUE

The water quality reaction equations in the PIONEER-I water quality routing model are solved by a Lagrangian solution technique, which employs a coordinate system that moves with a particle of water in its path down the stream. The Lagrangian coordinate system allows a relatively simple computational technique to be used and reduces the computer time required to solve a given problem. It also eliminates the numerical dispersion characteristic of Eulerian solutions of the transport equation in large river systems.

Although the Lagrangian approach does not imply steady-state conditions, the manner in which it is incorporated into the model allows only the investigation of steady-state conditions. This can be shown by examining the one dimensional transport equation:

$$V_x \frac{\partial L}{\partial x} + \frac{\partial L}{\partial t} + K_1 L = o \qquad (1)$$

where

V_x = velocity in the reach,

L = carbonaceous BOD concentration, and

K_1 = deoxygenation rate constant.

In the PIONEER-I model the equation is solved in Lagrangian coordinates, which gives

$$\frac{\partial L}{\partial t} = - K_1 L \qquad (2)$$

or upon integration

$$L = L_o e^{-K_1 t} \qquad (3)$$

The method used in selecting river reaches is such that waste inputs occur at junctions between each reach, and K_1 is a constant for the reach. The velocities and waste inputs are also considered constant with respect to time. The travel time through the reach is calculated from the channel velocity and substituted into Equation 3 to determine the degradation occurring through the reach. If the program were designed to keep track of multiple cells of water moving through the reaches and if the waste inputs were time varying, Equation 3 could be used to describe transient conditions. However, as the program is written only steady-state conditions can be handled because only one cell of water is followed through the reaches.

Since a steady-state analytical tool was requested, Equation 1 reduces to

$$V_x \frac{\partial L}{\partial x} = - K_1 L \tag{4}$$

for steady-state conditions, and upon integration gives

$$L = L_o \, e^{- \frac{K_1}{V_x} X} \tag{5}$$

For steady-state conditions, Equations 3 and 5 are identical, as shown by the relationship between Lagrangian and Eulerian coordinates,

$$X_e = X_L + V_x t \tag{6}$$

where

V_x = constant,

X_L = distance in Lagrangian coordinates, and

X_e = distance in Eulerian coordinates.

Using the chain rule on the Eulerian space derivative gives

$$\frac{\partial L}{\partial X_e} = \frac{\partial L}{\partial X_L} \frac{dX_L}{dX_e} + \frac{\partial L}{\partial t} \frac{dt}{dX_e} \tag{7}$$

By definition $\frac{dX_L}{dX_e} = 0$ and $\frac{dt}{dX_e} = \frac{1}{v_x}$ and Equation 7 reduce to

$$\frac{\partial L}{\partial X_e} = \frac{1}{v_x} \frac{\partial L}{\partial t} \qquad (8)$$

Substituting Equation 8 into the steady state Equation 4 gives

$$\frac{\partial L}{\partial t} = - K_1 L \qquad (9)$$

which is the same as Equation 2, providing the steady-state conditions exist.

In other words, for steady-state conditions, the BOD model should be written as Equation 4 rather than as Equation 2. However, the water quality models discussed in the next section will be written with time rather than distance as the independent variable, for three reasons: 1) the conditions under which one transforms into the other are known; 2) the PIONEER-I model is written in terms of Equation 2; and 3) the water quality models are normally written with time as the independent variable.

The main disadvantage of the PIONEER-I model is that dynamic solutions are not readily obtainable. Thus, diurnal effects or flushing effects cannot be studied in any detail.

WATER QUALITY MODELS

While developing another river basin water quality model Battelle reviewed and evaluated over 400 references relating to water quality modeling. The best models with respect to accuracy, input requirements, data availability and general applicability were selected and synthesized into an integrated model named EXPLORE-I[2] which handles 22 constituents. Except for fecal coliforms, all of the nonconservative parameters simulated in the PIONEER-I code were previously modeled in the EXPLORE-I code. The reaction equations for each of the water quality constituents considered in PIONEER-I are listed below.

The reaction equations for the models presented in the following subsections are written with time as the independent variable. This is the form in which the code

evaluates the reactions. However, the solution to these equations can be easily transformed to the distance down the stream as discussed previously.

Conservative Parameters

The modeling of conservative substances in steady-state systems is relatively simple because all reaction terms are dropped from the transport equations. Since a Lagrangian solution technique is used in PIONEER-I, only the increase or decrease in concentration due to hydraulic and quality sources must be considered. The water quality parameter concentrations are determined by a simple mass balance for each reach by the following equation:

$$C_n^i = \frac{C_{n-1}^i \, Q_{n-1} + \sum_k C_k^i \, Q_k}{Q_{n-1} + \sum_k Q_k} \qquad (10)$$

C_n^i = concentration of the i^{th} parameter in the n^{th} reach;

C^i_{n-1} = concentration of the i^{th} parameter in the n-1 reach (the reach upstream of the n^{th} reach);

C_k^i = concentration of the i^{th} parameter in the k^{th} source or tributary at the junction of the n-1 and n^{th} reach;

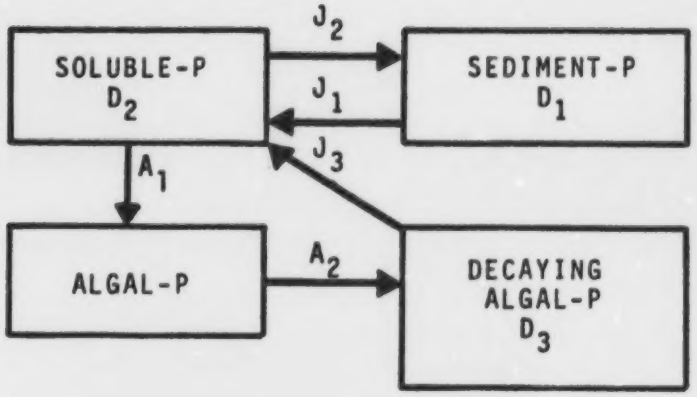
Q_{n-1} = flow rate in the n-1 reach; and

Q_K = flow rate of the k^{th} source or tributary at the junction of the n-1 and n^{th} reach.

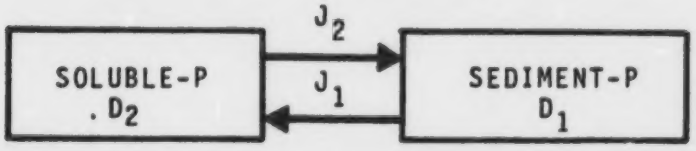
This method is used to determine the concentration of total dissolved solids, total nitrogen, and zinc.

Phosphorus

Both first-order and second-order reactions are available in the model. In those cases where algae are present in the river system and sufficient data are available, the model shown in Figure 1 can be used. This model is described by the following first-order equations:



a. ALGAL PHOSPHORUS MODEL



b. FIRST ORDER PHOSPHORUS MODEL

c. SECOND ORDER PHOSPHORUS MODEL

FIGURE 1. PHOSPHORUS MODELS

$$\frac{dD_1}{dt} = - J_1 D_1 + J_2 D_2$$

$$\frac{dD_2}{dt} = - J_2 D_2 + J_1 D_1 + J_3 D_3 - A_1 \qquad (11)$$

$$\frac{dD_3}{dt} = - J_3 D_3 + A_2$$

where

D_1 = areal concentration of phosphorus in sediments;

D_2 = concentration of phosphorus in soluble form;

D_3 = concentration of phosphorus in particulate organic form of dead algae;

J_1, J_2, J_3 = empirically determined rate constants;

A_1 = rate of algal utilization of phosphorus, calculated by algae model; and

A_2 = rate of algal death calculated by algae model.

Most of the phosphorus returned to the water from dead algal cells is released gradually as the algae decay. D_3 is used in the model to obtain the proper time delay in the release of the algal phosphorus.

In cases where algae are not significant or sufficient data on the algal mechanics are not available, the behavior of phosphorus can be described by a first-order reaction (see Figure 1b). Equation 11 will then reduce to

$$\frac{dD_1}{dt} = - J_1 D_1 + J_2 D_2 \qquad (12)$$

$$\frac{dD_2}{dt} = - J_2 D_2 + J_1 D_1$$

in which the notation remains the same.

A simple second-order model is incorporated into the system (Figure 1c) for use when data are not available for evaluating the constants in the model described above or when the data indicate that a second-order reaction is occurring. The model is described by the following equation

$$\frac{dD}{dt} = - J D^2 \qquad (13)$$

where

D = concentration of soluble and suspended phosphorus and

J = decay constant.

The PIONEER-I code includes all three of the above options and the appropriate mode is selected by the user. Default selection and values of the constants are included in the model to simplify the input when data are not available for evaluating the constants.

The temperature dependence of the phosphorus rate constants J_1, J_2 and J_3 are given by the equation:

$$J_i(T) = J_i(20)\ \theta^{(T-20)} \qquad (14)$$

where

$J_i(T)$ = the value of the i^{th} constant at temperature T;

$J_i(20)$ = the value of the i^{th} constant at 20°C;

θ = temperature constant and

T = temperature at 20°C.

Fecal Coliforms

Fecal coliform bacteria are modeled by a first-order decay equation of the form:

$$\frac{dC}{dt} = - k_c\ C \qquad (15)$$

where

C = fecal coliform concentration at time t;

C_o = initial coliform concentration;

k_c = decay constant.

The temperature dependence of the rate constant is given by:

$$k_c\ (T) = k_c\ (20)\ \theta^{(T-20)} \qquad (16)$$

where

$k_c(T)$ = decay constant at emperature T °C;

$k_c(20)$ = decay constant at 20°C;

θ = temperature constant; and

T = temperature in °C.

Nitrogen

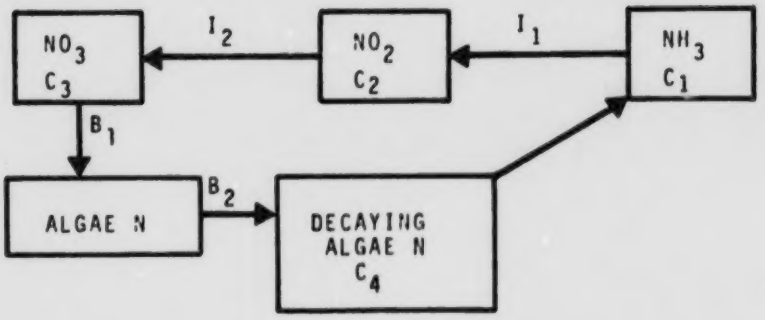
Two different models of nitrogen have been included in the PIONEER-I code. When sufficient algae data are available, the model shown in Figure 2a can be used. This model can be described by the following first order equations:

$$\frac{dC_1}{dt} = - I_1C_1 + I_3C_4$$

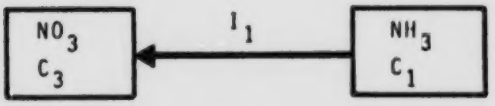
$$\frac{dC_2}{dt} = - I_2C_2 + I_1C_1 \qquad (17)$$

$$\frac{dC_3}{dt} = + I_2C_2 - B_1$$

$$\frac{dC_4}{dt} = - I_3C_4 + B_2$$



a. ALGAL NITROGEN MODEL



b. FIRST ORDER NITROGEN MODEL

FIGURE 2. NITROGEN MODELS

where

C_1 = concentration of ammonia nitrogen;

C_2 = concentration of nitrite nitrogen;

C_3 = concentration of nitrate nitrogen;

C_4 = concentration of nitrogen in decaying algae;

I_1, I_2, I_3 = empirically determined rate constants;

B_1 = rate of algal utilization of nitrogen calculated by the algal model; and

B_2 = rate of algal death calculated by the algal model.

The nitrogen in decaying algae is accounted for separately to obtain the proper time delay in nitrogen release from decaying algae.

In many cases algae are not present or a lack of data precludes the use of algal interaction with nitrogen, so a simple oxidation scheme (as shown in Figure 2b) can be used. The equations for this model are

$$\frac{dC_1}{dt} = - I_1 C_1 \tag{18}$$

$$\frac{dC_3}{dt} = + I_1 C_1$$

with notation as specified for Equation 17.

The dissolved oxygen used in the ammonia and nitrite oxidation process is determined stoichiometrically from the following equations.

$$NH_4^+ + \frac{3}{2} O_2 \rightarrow NO_2^- + 2H^+ + H_2O \tag{19}$$

$$NO_2^- + \frac{1}{2} O_2 \rightarrow NO_3^- .$$

The dissolved oxygen consumed by oxidation of ammonia and nitrite is transferred to the dissolved oxygen model.

The effect of temperature on the nitrogenous oxidation process is accounted for by the expression:

$$J_i(T) = J_i\ (20)\ \theta^{T-20} \tag{20}$$

where

$J_i(T)$ = i^{th} rate constant of temperature T;

$J_i(20)$ = i^{th} rate constant at 20°C;

θ = empirically derived constant;

T = temperature °C.

Carbonaceous Biochemical Oxygen Demand (BOD)

The suspended and dissolved BOD is described by the equation:

$$\frac{dL}{dt} = - (k_1 + k_3) L + P \qquad (21)$$

where

L = carbonaceous BOD concentration;

k_1 = deoxygenation rate constant;

k_3 = sedimentation rate constant for suspended BOD; and

P = scour of BOD from the river bottom.

The temperature dependence of the deoxygenation coefficient k_1 is given by:

$$k_1(T) = k_1(20)\ \theta^{(T-20)} \qquad (22)$$

where

$k_1(T)$ = k_1 at temperature T °C;

$k_1(20)$ = k_1 at 20°C;

θ = constant.

Algae Model

The modeling of algae is inherently complex because of the heterogeneous algal populations and the myriad of interacting environmental factors that influence algal dynamics. Algae have been separated into two categories, planktonic (unattached) algae and sessile (attached) algae. Sessile algae, attached plants, and other micro- and macro-organisms residing on the bottom of the watercourse are collectively classified as benthic organisms. This model of the South Platte River Basin is concerned primarily with the modeling of phytoplankton as represented by chlorophyll a concentration.

Analysis of early algae models has identified six physical and environmental factors which affect algal growth and death:

- irradiance
- depth
- temperature
- nutrients
- predators
- vertical turbulence

The number of trophic levels included in the model can also change the results of model predictions.

Most phytoplankton models are based on calculation of the growth and death rates of the algae, coupled with a system of equations describing the predator and prey relationships. These models, however, predict long-term (weeks or months) dynamics of the plankton community. Steady-state models applicable to the modeling effort proposed here have not, in general, been attempted.

The PIONEER-I model considers the growth and death of phytoplankton based on the following equation:

$$\frac{dP}{dt} = (G-D)\ P \qquad (23)$$

where

P = phytoplankton concentration;

G = phytoplankton growth rate; and

D = phytoplankton death rate.

Numerous forms of growth and death terms have been used in previous models. One of the most complete forms is given by DiToro, et al.[3];

$$G = [F_1 T] \times \left[\frac{2.718f}{k_e H}\left(e^{-\alpha_1} - e^{-\alpha_o}\right)\right] \times \left[\frac{N}{K_N+N} \cdot \frac{D}{K_D+D}\right]$$

$$D = F_2 T + F_3$$

where

F_1 = saturated growth rate of phytoplankton;

F_2 = respiration rate of phytoplankton;

F_3 = death of phytoplankton due to other causes;

T = temperature;

f = average photoperiod;

k_e = extinction coefficient;

H = average water depth;

$\alpha_1 = (I_a/I_s) \exp \{-k_e H\}$;

$\alpha_o = I_a/I_s$;

I_a = average irradiance incident on water surface;

I_s = irradiance at which saturated growth occurs;

N = nitrogen concentration;

K_N = Michealis' constant for nitrogen;

D = phosphorus concentration;

K_D = Michealis' constant for phosphorus.

The growth rate considers three effects. The first factor represents the normal saturated growth of the phytoplankton as a function of temperature. The second factor considers the reduction in growth due to the average irradiance available to the phytoplankton for photosynthesis. The third factor accounts for the decrease in growth rate due to nutrient deficiency (phosphorus and nitrogen). The death rate has been simplified to eliminate the zooplankton concentration included in the original model.

Although the model appears formidable at first glance, it is one of the simplest available which considers all of the important factors. Because of this completeness, confidence in the model to reliably predict situations other than the calibration conditions should be greater than if simpler models were used.

Dissolved Oxygen (DO)

The dissolved oxygen concentrations in a stream are influenced by a variety of interrelated factors, of which the most important are

- bacterial oxidation of organic matter
- benthic demand
- algal photosynthesis and respiration
- reaeration
- temperature

The first four categories represent more or less independent phenomena, all of which are influenced by temperature. The equation for the dissolved oxygen represents a mass balance of these sinks and sources:

$$\frac{dDO}{dt} = - \text{(BOD use)} - \text{(Benthic use)} \pm \text{(Algal production or use)} \pm \text{(Reaeration)} \quad (26)$$

The use of oxygen by degradation of carbonaceous BOD is given by the expression:

$$BOD_C = k_1 L \text{ mg/l/day} \quad (27)$$

The carbonaceous BOD concentration (L) as a function of river reach is computed by the BOD model.

For nitrogenous oxidation, the stoichiometric coefficients are used to convert to oxygen use:

$$BOD_N = I_1C_1N_. + I_2C_2N_2 \text{ mg/l/day} \quad (28)$$

where

C_1 = concentration of ammonia nitrogen;

C_2 = concentration of nitrite nitrogen;

I_1, I_2 = rate constants; and

N_1, N_2 = stoichiometric coefficients relating oxygen to ammonia nitrogen and nitrite nitrogen, respectively.

The ammonia and nitrite concentrations are computed as a function of river reach by the nitrogen model.

In any steady-state model, the benthic demand must be input in the form of an areal demand, B_e, $g/m^2/day$. The benthic demand is computed by the following relationship:

$$\text{Benthic} = \frac{B_e}{H} \text{ mg/l/day} \qquad (29)$$

where H is the river depth. The benthic demand is input for each river reach.

Diurnal variation of the DO levels due to phytoplankton cannot be easily described in a steady-state model. Instead, the net DO produced in a 24 hour period must be used. Two models are available with the PIONEER-I code. First, if algae calculations are being used by the model, the net DO production will be given by:

$$(P\text{-}R)_{Net} = a\ P \qquad (30)$$

where

$(P\text{-}R)_{Net}$ = Net DO production;

a = proportionality constant; and

P = phytoplankton concentration.

The phytoplankton (chlorophyll a) concentration is calculated by the algae model. If no algae calculations are being performed, the net DO production is input as a constant for each reach of the river.

The prediction of reaeration rates (k_2) is a very important part of any DO balance in a river system. The PIONEER-I model provides four reaeration models for each reach:

- specific k_2 value;
- velocity and depth exponent model;
- flow exponent model; and
- Thackston-Krenkel slope dependent model.

A specific value of k_2 may be read into the program if, for example, field surveys have been made at particular flows and values of the reaeration coefficient have been computed from the results. This option must be used with caution since the reaeration coefficient is generally a function of stream properties such as water velocity and depth.

The second option is based on observation that the reaeration rate coefficient is directly proportional to the mean stream velocity and inversely proportional to the mean depth. This relationship assumes that increasing velocity and turbulence increases the surface renewal rate of dissolved oxygen and promotes mixing and dispersion of the oxygen throughout the depth of the stream.

In addition, increased depth decreases the rate of dispersion of dissolved oxygen throughout the water mass, thus resulting in lower quantities of oxygen being transferred from the atmosphere.

Therefore

$$k_2 = a \frac{v^b}{h^c} \qquad (31)$$

where

v = velocity (ft/sec)

h = depth (ft)

a,b,c = regression coefficients

Numerous investigators have determined the coefficients for use in Equation 31 to calculate the reaeration coefficient for any stream in which the mean velocity and mean depth are known. Table 1 presents these coefficients as determined by five investigators in both field and laboratory tests. The coefficients developed by Churchill in 1962 and by Langbein and Durum in 1967 are probably the best known for the computation of the reaeration rate coefficient for general model use.

TABLE 1

COEFFICIENTS FOR COMPUTATION OF THE REAERATION COEFFICIENT

Investigator	Reference	A_3	B_3	C_3
Churchill, et al.	4	5.026	0.969	1.673
Langbein and Drun	5	3.3	0.50	1.33
O'Connor and Dobbins	6	12.90	0.50	1.50
Owens and Gibbs	7	9.4	0.67	1.85
Bansal	8	4.6	0.6	1.4

The third option for computing the reaeration coefficient is given by

$$k_2 = aQ^b \qquad (32)$$

where

Q = flow (cfs)

a, b = regression coefficients

At the present time no generally acceptable values for a and b are available because many of the factors which affect reaeration are not adequately described by a simple relationship with stream flow.

The fourth option is based on a formulation by Thackston and Krenkel.[9] The relationship is given as:

$$k_2 = 0.000125 \left(1 + \left(\frac{v}{(gd)^{1/2}}\right)^{1/2}\right) \cdot (S)^{1/2} \left(\frac{g}{d}\right) \qquad (33)$$

where

v = velocity (ft/sec);

g = gravity constant (32.2 ft/sec^2);

d = depth (ft); and

S = slope (ft/ft).

The slope is input by the user. This formulation is based primarily on laboratory data.

The reaeration coefficient calculated by the above equations is corrected for temperature based on the equation:

$$k_2\ (T) = k_2\ (20)\ (1.0159)^{(T-20)}$$

where

$k_2\ (T)$ = reaeration coefficient at temperature T ^{o}C;

$k_2\ (20)$ = reaeration coefficient at $20^{o}C$; and

T = temperature, ^{o}C.

The contribution of dissolved oxygen due to reaeration is calculated by:

$$\text{Reaeration} = k_2\ (DO_{Sat} - DO) \qquad (34)$$

where

DO_{Sat} = saturated DO concentration at the temperature and elevation of the reach; and

k_2 = reaeration calculated by one of the four models given above.

The actual DO equation is then written as:

$$\frac{dDO}{dt} = - k_1 L - (I_1 C_1 N_1 + I_2 C_2 N_2) - \frac{B_e}{H} + a\ P + k_2\ (DO_{Sat} - DO) \qquad (35)$$

General N^{th} Order Reaction Model

Although not specifically requested, a general N^{th} order reaction model has been incorporated in the PIONEER-I model to allow the user the flexibility of using higher order reaction kinetics. The equation describing this model is:

$$\frac{dS}{dt} = - KS^{n} \qquad (36)$$

where

n = any real number specified by the user;

S = concentration of specific compound; and

K = rate constant.

This model can be used in place of the BOD, nitrogen and phosphorus models or can be used to study the distribution of various toxic or other compounds in the river system. Inclusion of this model adds negligible computer running time or input complication, and may prove very useful at a later time in analyzing miscellaneous reactions in the stream.

Integrated Water Quality Models

The integrated water quality models are shown in Figure 3. The set of differential equations presented above are solved along each reach using a fourth order Runge-Kutta procedure. This solution technique is computationally fast, yet accurate enough for the relatively slowly varying functions used in the water equations.

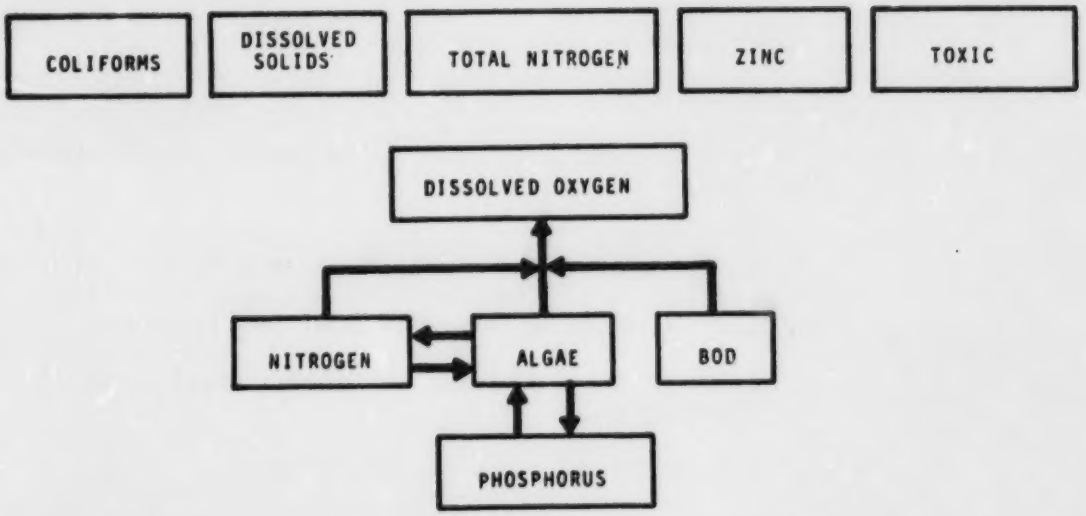


FIGURE 3. INTEGRATED WATER QUALITY MODELS

PROGRAM SETUP AND OPERATION

The river basin being modeled must be divided into a number of discrete elements for input into the PIONEER-I program. These elements are defined in the DOSAG-I code as follows:

(1) junctions - the confluence of two streams within the river basin being simulated;

(2) stretches - the portion of a river between junctions;

(3) headwater stretches - the length of a river or stream from its headwater to its first junction with another stream; and

(4) reaches - the subunits into which a stretch is divided (either headwater stretches or regular stretches).

Normally a reach is defined as any place in a stretch where there is a significant change in the hydraulic, biological, or physical characteristics of the river, the addition of a waste load, or the withdrawal of water from the river. The PIONEER-I code requires that the headwater stretches be numbered consecutively, beginning with one. The non-headwater stretches can be numbered in any manner. The current PIONEER-I code has the following restrictions:

(1) maximum number of headwater stretches = 25;

(2) maximum number of junctions = 25;

(3) maximum number of reaches = 300;

(4) maximum number of stretches = 50;

(5) maximum of twelve months of routing for temperature and headwater flows

(6) maximum number of dissolved oxygen targets = 4 (a minimum of one dissolved oxygen target must be specified, which may be entered as a negative number if no flow augmentation is desired);

(7) maximum of five degrees of treatment for waste influents; and

(8) a maximum of 40 reaches per stretch.

The methods of input for the hydraulic and physical characteristics and the models of reaeration for the reaches in the stream system being simulated are essentially the

same as they were for DOSAG-I and are not discussed here. The handling of waste discharges and diversions is also identical to DOSAG-I. Further details will be found in Appendix A and reference 1.

With DOSAG-I, temperatures for all reaches in the simulation were the same and this temperature value was input via the file H card (File H - Mean Monthly Temperatures). The use of a uniform temperature over the entire South Platte River Basin is not a valid assumption, however, and PIONEER-I requires that temperature be input for each reach on the file F-3 cards (see Appendix A). In order to facilitate the multiple run capability available with DOSAG-I the file H cards in PIONEER-I now specify a mean monthly temperature factor. The temperature for each reach is then calculated in PIONEER-I by multiplying the reach temperature input on the file F-3 card by the mean monthly temperature factor specified for the current run on the file H card.

PIONEER-I offers a choice of quality models to be used in the simulation. File J has been added to allow the PIONEER-I user to select the desired quality models. The options available and input formats are discussed in detail in Appendix A.

The quality models used in PIONEER-I require the input of 30 coefficients in addition to the reaeration coefficients necessary to calculate K_2. In DOSAG-I, the quality models for carbonaceous and nitrogenous biochemical oxygen demand require only two coefficients per reach. These coefficient values had to be input for each reach even though the values selected were very often the same. In order to make input of the quality model coefficients easier and yet retain the flexibility of different sets of these values for each reach, PIONEER-I allows the user to define what might be called "coefficient reaches". By specifying an upstream stretch number, SN1, and the associated reach number, RN1, and a downstream stretch number, SN2, and the associated reach number, RN2, the user has defined a "coefficient reach". All of the reaches in the flow path between reach RN1 and RN2 and including RN1 and RN2 will have the same quality model coefficients. The details of input format and an example are included in Appendix A.

SECTION V

CALIBRATION OF THE PIONEER-I MODEL ON THE SOUTH PLATTE RIVER BASIN

Setup and calibration of the PIONEER-I code on the South Platte River Basin was a major effort of the present program. Figure 4 shows a layout of the portion of the Basin that was modeled. This layout required 43 stretches (22 of which are headwater stretches), 21 junctions, and 271 reaches. The locations and available data for all the diversions, industrial wastes, municipal wastes, and other inflows used in the South Platte simulation are thoroughly documented and discussed in the Data Report.

For the purpose of calibration, two separate time periods were used which correspond to the two relatively different sets of conditions during which serious water quality problems are generally experienced in the South Platte River Basin. The first time period occurs in late summer when streamflows are low and water temperatures high. The second period occurs in late fall and early winter when the sugar beet processing industry is in full swing.

The late summer period chosen for calibration purposes was August 1971. During this period an intensive effluent stream water quality survey was conducted by the EPA, making a comprehensive set of water quality data available. To verify this calibration, calculations were made using streamflow and water quality data taken in August 1970. The late fall time period was selected as December of 1970. Water quality data taken in December 1971 were used in conjunction with streamflow data from December 1970.

HYDRAULIC INPUT

The following parameters must be determined to specify the hydraulic input:

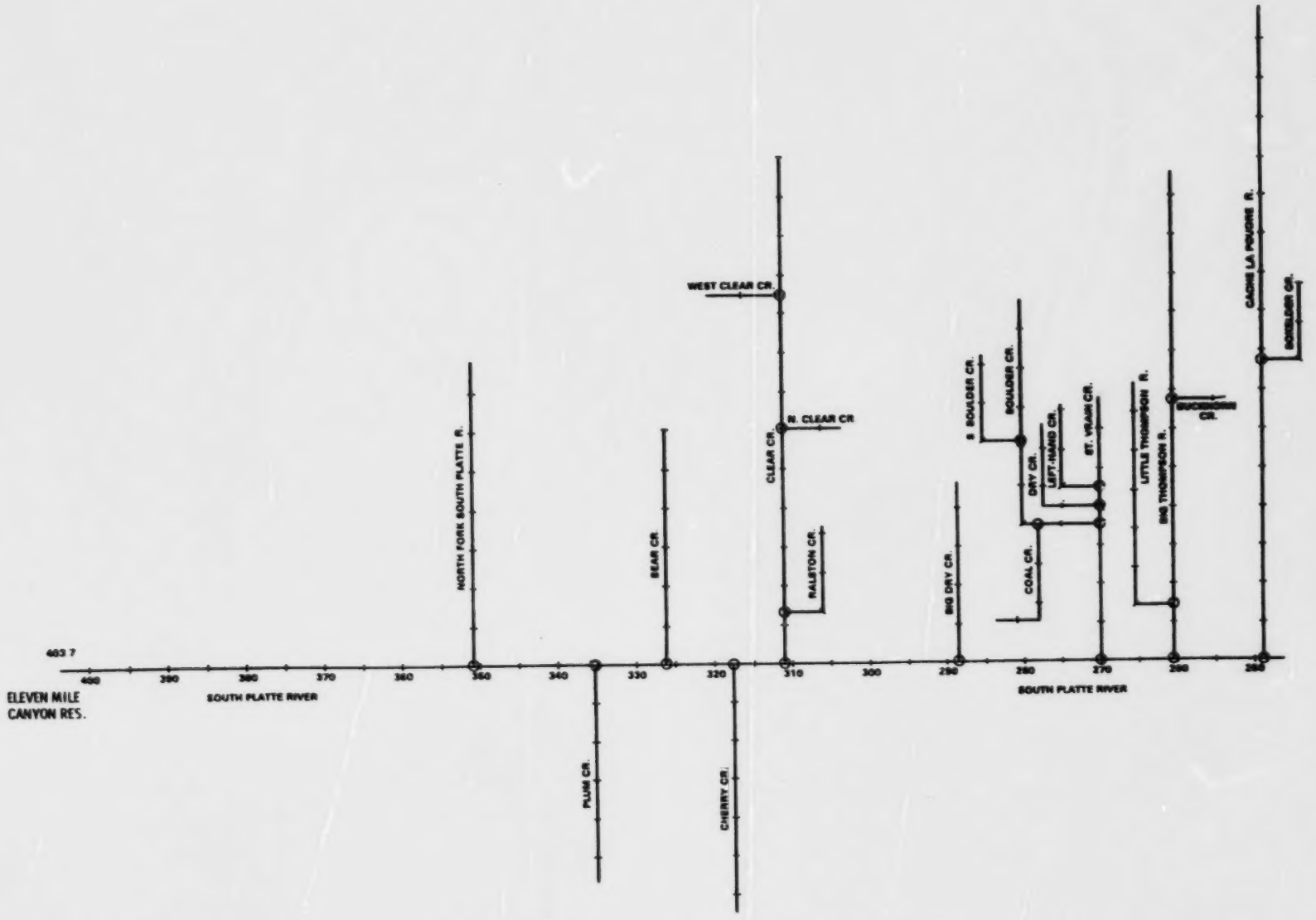


FIGURE 4. PIONEER-I MODEL LAYOUT - SOUTH PLATTE BASIN

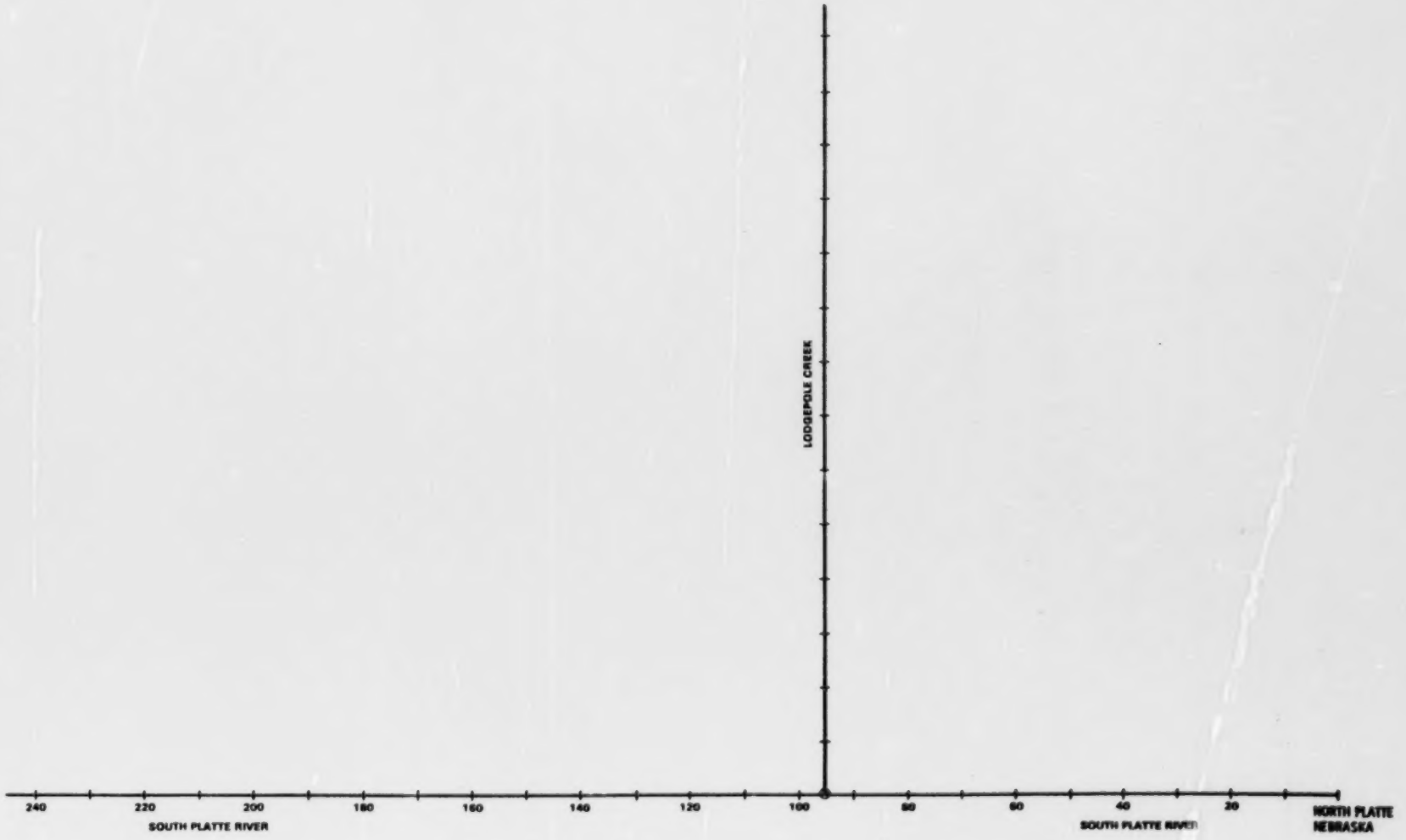


FIGURE 4. PIONEER-I MODEL LAYOUT - SOUTH PLATTE RIVER BASIN (CONTINUED)

- regression coefficients for velocity versus flow;
- regression coefficients for depth versus flow;
- headwater flows;
- point source inflows (canals, municipal and industrial effluents, streams);
- point source withdrawals (irrigation diversions, municipal and industrial water supplies);
- distributed inflows (groundwater inflows and overland runoff); and
- distributed withdrawals (losses to groundwater).

Regression Coefficients

PIONEER-I simulates the hydraulic characteristics (depth and velocity) of each river reach using Ward's equations:

$$V = a\ Q^{b} \tag{37}$$

$$D = a_1\ Q^{b_1} \tag{38}$$

where

V = mean velocity in the river reach (ft/sec);

Q = mean flow in the river reach (cfs);

D = mean depth of the water in the reach (ft); and

a, b, a_1, b_1 = regression coefficients.

In the South Platte River Basin, measurements of the average depths and velocities at different flow rates have been made at numerous gauging stations. These historical data were obtained and correlated with a non-linear regression program, LEARN.[9] Table 2 lists the regression coefficients obtained in this manner. In many cases extensive reaches of river lay between two gauging stations and one must question the applicability of such regression coefficients to the entire length of a reach. Since the collection of data in

TABLE 2

REGRESSION COEFFICIENTS CALCULATED BY BNW LEARN FOR DEPTH AND VELOCITY AT THE HYDROLOGIC GAUGING STATIONS IN THE SOUTH PLATTE RIVER BASIN

ID NO.	USGS Station Number	Location	Regression Coefficients			
			a_d	b_d	a_v	b_v
1	06701500	Below Cheesman Lake, Colo.	.520	.209	.217	.468
2	06707500	South Platte, Colo.	.340	.345	.382	.316
3	06708000	Waterton, Colo.	.395	.228	.277	.395
4	06710000	Littleton, Colo.	.929	.265	.546	.282
5	06714000	Denver, Colo.	.996	.171	.468	.278
6	06720500	Henderson, Colo.	.532	.278	.539	.248
7	06754000	Kersey, Colo.	.503	.298	1.020	.131
8	06758500	Weldona, Colo.	.852	.245	.840	.163
9	06760000	Balzac, Colo.	.882	.263	.874	.174
10	06764000	Julesburg, Colo.	.997	.216	.928	.156
11	06706000	Grant, Colo.	.305	.276	.734	.158
12	06707000	South Platte, Colo.	.952	.205	.190	.496
13	06709500	Plum Creek, Colo.	2.123	.043	1.369	.197
14	06710500	Morrison, Colo.	1.784	.245	.660	.278
15	06711500	Sheridan, Colo.	.494	.254	.417	.430
16	06712000	Cherry Creek, Colo.	.680	.675	.908	.365
17	06716500	Clear Creek, Colo.	.822	.278	.240	.454
18	06719500	Golden, Colo.	.566	.323	.208	.470
19	06720000	Derby, Colo.	.575	.316	.184	.471
20	06724000	Lyons, Colo.	1.951	.124	.212	.496
21	06727000	Orodell, Colo.	.971	.198	.105	.615
22	06729500	Eldorado Springs, Colo.	1.003	.194	.327	.514
23	06730300	Plainview, Colo.	.605	.208	.376	.527
24	06731000	Platteview, Colo.	.499	.294	.714	.188
25	06738000	Drake, Colo.	.494	.283	.175	.519
26	06744000	La-Salle, Colo.	.412	.335	.410	.303
27	06752000	Ft. Collins, Colo.	.517	.282	.462	.280
28	06752500	Greeley, Colo.	.440	.335	.855	.170

the field was beyond the scope of this project, a study was made to determine whether the use of a simple hydraulic calculation based on Manning's equation could improve the regression coefficients between the measured stations.

Manning's equation is given as:

$$v = \frac{1.49R^{2/3}S^{1/2}}{n} \tag{39}$$

Where:

v = velocity (ft/sec);

R = hydraulic radius (ft);

S = energy gradient slope (ft/ft); and

n = Manning's coefficient.

The study was done for five gauging stations in the South Platte Basin, gauges 7, 8 and 9 on Clear Creek and gauges 18 and 19 on the South Platte River. Manning's equation and data collected from USGS topographic maps were used to calculate the velocity and depth at the five gauges studied for various values of Manning's coefficient and June 1971 flow conditions. Comparisons were then made between the values for stream width, water depth, and velocity measured at the gauge stations and those computed with Manning's equation and the data from the topographic maps. Table 3 shows the results of this comparison.

In comparing the river widths measured at the gauging stations with those determined from topographic maps, significant disagreement was found. If the calculations using Manning's equation are repeated using the river widths measured at the stations (instead of those taken from the topographic maps), the agreement between velocities and depths is better (i.e., for a given Manning's coefficient the predicted velocity and depth were slightly closer to the measured values).

By algebraic manipulation Manning's equation can be put into a form similar to Ward's equation as follows:

$$v = \frac{1.49R^{2/3}S^{1/2}}{n} \tag{40}$$

TABLE 3

COMPARISON BETWEEN MEASURED VALUES
AND CALCULATED VALUES USING MANNING'S EQUATION

	GAUGE STATION DATA				TOPOGRAPHIC AND CALCULATED DATA									
							Man = 0.02 Coef.		Man = 0.03 Coef.		Man = 0.04 Coef.		Man = 0.05 Coef.	
Gauge Identification and Date	Flow (cfs)	Width (ft)	Velocity (fps)	Water Depth (ft)	Width (ft)	Slope 1000 (ft)	Vel (fps)	Water Depth (ft)	Vel (fps)	Water Depth (ft)	Vel (fps)	Water Depth (ft)	Vel (fps)	Water Depth (ft)
7 June 14	1180.	244.	2.79	1.73	184.	0.714	3.2	2.0	2.5	2.6	2.1	3.1	1.8	3.5
8 June 10	751.	198.	2.54	1.49	104.	1.020	3.8	1.8	3.0	2.4	2.6	2.8	2.2	3.3
9 June 8	517.	109.	2.64	1.80	168.	1.316	2.8	1.1	2.2	1.4	1.9	1.6	1.6	1.9
18 June 17	1220.	87.5	5.62	2.48	91.	8.571	9.0	1.5	7.1	1.9	5.9	2.3	5.2	2.6
19 June 18	858.	85.0	3.90	2.55	69.	3.571	6.8	1.8	5.4	2.3	4.5	2.8	3.9	3.2

but $Q = v \cdot A = v \cdot d \cdot w$ (41)

where Q = flow (cfs);

A = flow cross sectional area (ft^2);

d = mean depth (ft); and

w = mean width.

If we assume $R = d$ then

$$\frac{Q}{d \cdot w} = \frac{1.49\ d^{2/3} S^{1/2}}{n} \tag{42}$$

or

$$d = \left(\frac{n}{1.49 w S^{1/2}}\right)^{0.6} Q^{0.6} \tag{43}$$

and since

$$d = \frac{Q}{vw} \tag{44}$$

$$v = \left(\frac{1.49\ S^{1/2} n}{w^{2/3}}\right)^{0.6} Q^{0.4} \tag{45}$$

A set of "regression coefficients" derived from Manning's equation can now be calculated based on given values of river width and slope and Manning's coefficient. Table 4 compares the coefficients from these two equations when the velocities and depths are exactly matched for the flow rate given. Once again, if the river widths measured at the gauging stations are used in Manning's formulation instead of those measured from the topographic maps, the match of the coefficients is somewhat better since the predicted coefficients for both velocity and depth were slightly closer to those determined by regression from the measured data. Figures 5 - 9 show the velocities calculated using the regression coefficients given in Table 3. However, it is evident from these figures that in general the predicted velocities agree only within a very small range of flows.

TABLE 4

COMPARISON BETWEEN REGRESSION COEFFICIENTS
PREDICTED WITH MANNING'S EQUATION AND WARD'S EQUATION

Gauge Number	Manning Coefficient	PREDICTED REGRESSION COEFFICIENTS							
		STAGE				VELOCITY			
		Manning		Ward		Manning		Ward	
		Coefficient	Exponent	Coefficient	Exponent	Coefficient	Exponent	Coefficient	Exponent
7	.025	.0335	.6	.503	.298	.162	.4	1.08	.131
8	.039	.0531	.6	.852	.245	.181	.4	.840	.163
9	.022	.0273	.6	.882	.263	.218	.4	.874	.174
18	.044	.0336	.6	.566	.323	.328	.4	.208	.470
19	.051	.0556	.6	.575	.316	.261	.4	.184	.471

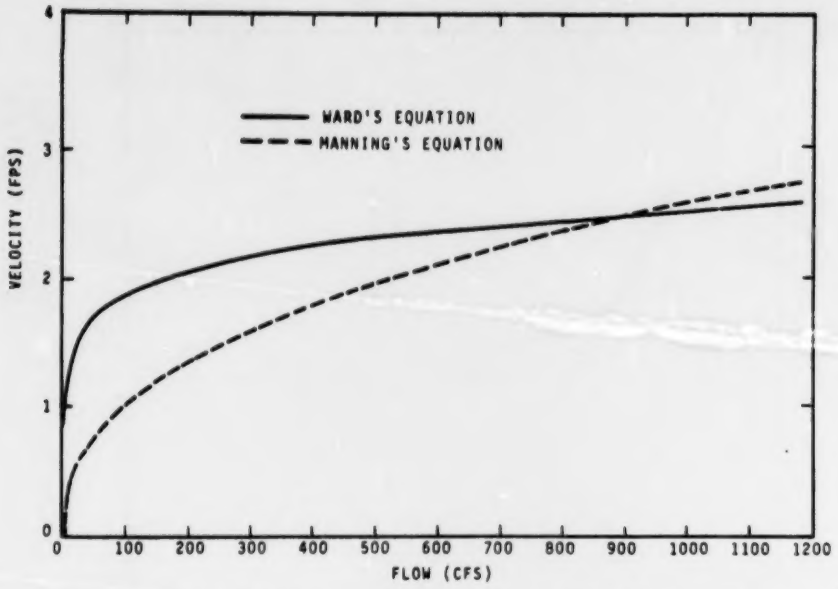


FIGURE 5. COMPARISON OF PREDICTED VELOCITIES FOR WARD'S AND MANNING'S EQUATIONS FOR GAUGE 7

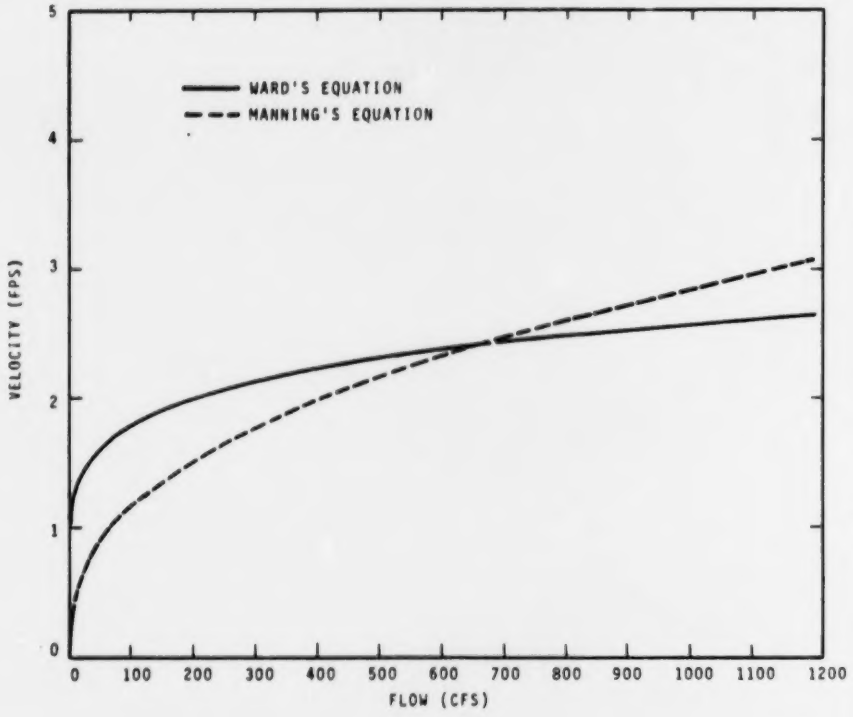


FIGURE 6. COMPARISON OF PREDICTED VELOCITIES FOR WARD'S AND MANNING'S EQUATIONS FOR GAUGE 8

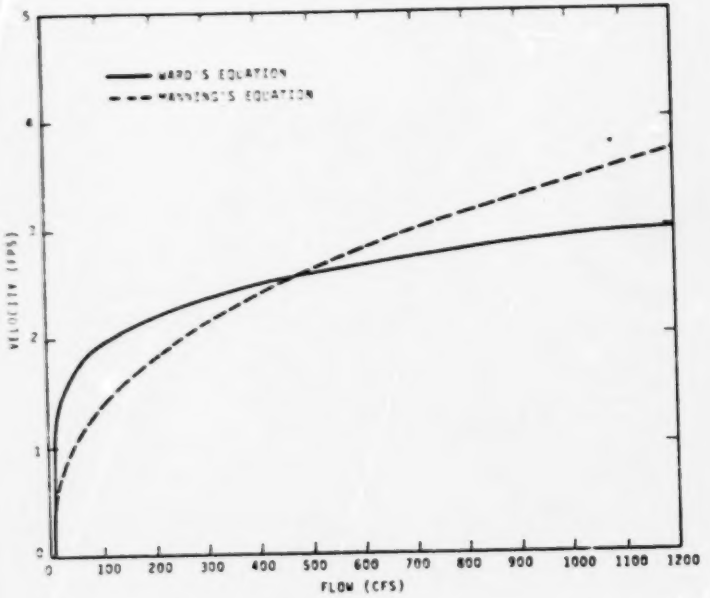


FIGURE 7. COMPARISON OF PREDICTED VELOCITIES FOR WARD'S AND MANNING'S EQUATIONS FOR GAUGE 9

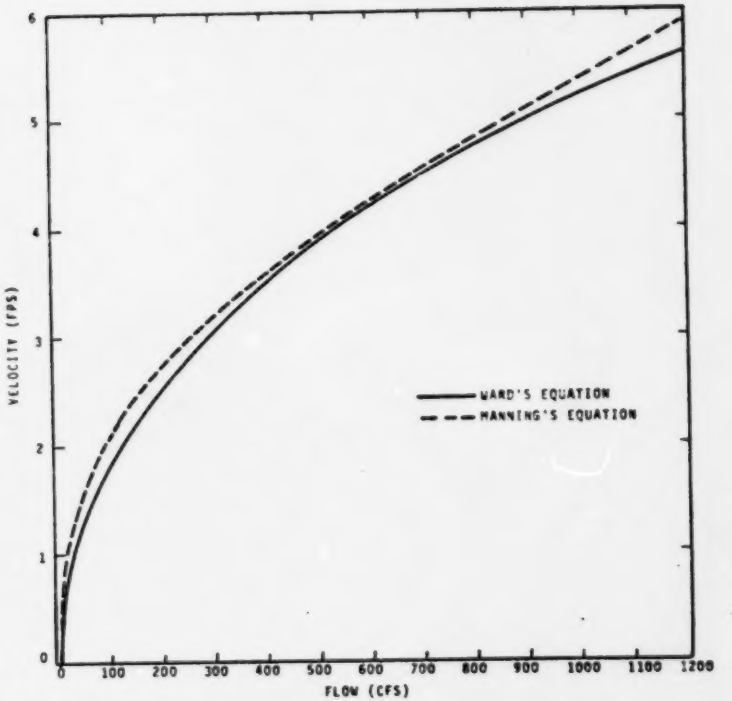


FIGURE 8. COMPARISON OF PREDICTED VELOCITIES FOR WARD'S AND MANNING'S EQUATIONS FOR GAUGE 18

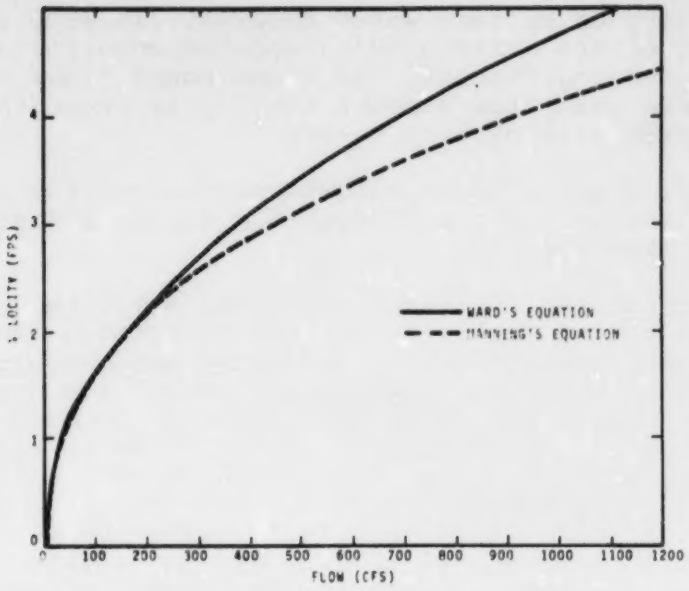


FIGURE 9. COMPARISON OF PREDICTED VELOCITIES FOR WARD'S AND MANNING'S EQUATIONS FOR GAUGE 19

Since reasonably good correlations could not be determined from Manning's equations, it was felt that the best general approach was to divide the river stretch between any two gauge sites in half and simply assign all reaches in the half closest to the upstream gauge the regression coefficients calculated for that gauge and all reaches in the half closest to the downstream gauge the regression coefficients calculated for that gauge. River reaches upstream from the uppermost gauge site were assigned those regression coefficients calculated for the uppermost gauge. In assigning values of the regression coefficients an attempt was made to consider any abrupt changes in hydraulic characteristics. In addition, rivers or streams which had no gauge stations were assigned regression coefficients from the gauges on streams which were determined to be most similar to the stream in question.

Flow Data

Most of the data on the flows at the headwaters of the major tributaries in the basin were obtained from USGS publications of surface water records. In some cases branching of the streams being modeled occurred upstream of the recording station. In these cases flows were distributed among the streams roughly in proportion to the drainage area of each branch.

Point inflow and withdrawal data were known for all significant points. The Data Report contains a discussion of these data sources.

Data covering the distributed inflows and withdrawals for the years of interest were not available. In order to determine these flows, a "detailed water balance" was performed on each length of river between two gauging stations. Water was added or subtracted to make the flows match at the downstream station. As an example, a detailed water balance calculation using the flows for August 1971 for the South Platte River from Henderson, Colo. (river mile 301.4, gauging station number 6) to Kersey, Colo. (river mile 246.1, gauging station number 7) is shown in Table 5. The result of this balance shows that a water deficit of 364.6 cfs exists at the downstream station at Kersey. Dividing this flow by the number of river miles between the two stations, 55.3 miles, it is determined that 6.59 cfs/mile must be added to the river. This value is then uniformly added along the river between the two gauge stations as is also shown in Table 5.

TABLE 5

DETAILED WATER BALANCE CALCULATION FOR SOUTH PLATTE RIVER FROM HENDERSON TO KERSEY, COLORADO

KNOWN POINT SOURCE FLOW DATA				CALCULATED INCREMENTAL RUNOFF FLOW		
LOCATION BY RIVER MILE	POINT SOURCE DESCRIPTION	FLOW IN cfs	FLOW OUT cfs	REACH LENGTH, MILES	INCREMENTAL RUNOFF INPUT TO CODE	IN STREAM FLOW CALCULATED BY CODE
301.4	GAUGE NO. 6	458.5	→			458.5
				← 3.9	25.7	484.2
297.5	DIVERSION		29.4 ←			454.8
295.8	WASTE SOURCE	2.9		← 1.7	11.2	466.0
295.6	WASTE SOURCE	0.0		← 0.2	1.3	468.9
						470.2
				← 3.7	24.4	494.6
291.9	DIVERSION		67.7 ←			426.9
				← 3.3	21.8	448.7
288.6	TRIBUTARY	11.0	→			459.7
287.6	WASTE SOURCE	0.1	→	← 1.0	6.6	466.3
286.9	DIVERSION		60.6 ←	← 0.7	4.6	466.4
						471.0
				← 3.2	21.1	410.4
283.7	DIVERSION		173.0 ←			431.5
						258.5
				← 4.0	26.4	284.9
279.7	DIVERSION		40.2 ←			244.7
				← 3.0	19.8	264.5
276.7	DIVERSION		64.1 ←			200.4
				← 3.3	21.8	222.2
273.4	DIVERSION		12.1 ←			210.1
272.2	DIVERSION		96.5 ←	← 1.2	7.9	218.0
						121.5
				← 2.2	14.5	136.0
270.0	TRIBUTARY	210.4	→			346.4
				← 4.6	30.3	376.7
265.4	DIVERSION		110.0 ←			266.7
				← 3.1	20.4	287.1
262.3	DIVERSION		37.7 ←			249.4
				← 1.9	12.5	261.9
260.4	TRIBUTARY	130.3	→			392.2
				← 3.7	24.4	416.6
256.7	DIVERSION		185.0 ←			231.6
				← 2.9	19.1	250.7
253.8	DIVERSION		19.8 →			230.9
				← 2.8	18.5	249.4
251.0	DIVERSION		21.2 ←			228.2
				← 2.0	13.2	241.4
249.0	TRIBUTARY	66.5	→			307.9
				← 2.9	19.1	327.0
246.1	GAUGE NO. 7		327.0 ←			
	TOTAL	879.7	1244.3	55.3	364.6	0.0 = BALANCE

FLOW DEFICIT = 1244.3 - 879.7 = 364.6 cfs

RIVER LENGTH BETWEEN GAGE STATIONS = 55.3 miles

REQUIRED INCREMENTAL RUNOFF = $\frac{364.6 \text{ cfs}}{55.3 \text{ miles}}$ = 6.59 cfs/mile

CALIBRATION OF MODEL FOR THE SUMMER PERIOD

Calibration of the PIONEER-I model was performed on each of the following rivers in the basin.

- South Platte River
- Clear Creek
- Boulder Creek
- St. Vrain Creek
- Big Thompson River
- Cache la Poudre River

On each of these rivers the following water quality parameters were considered in the calibration.

- Carbonaceous Biochemical Oxygen Demand (BOD)
- Ammonia (NH_3)
- Nitrate (NO_3)
- Total Phosphorus (P)
- Total Dissolved Solids (TDS)
- Dissolved Oxygen (DO)

This model could not be calibrated on the other streams in the basin due to a lack of flow and water quality measurements, but this does not detract from the usefulness of the model as applied to the entire South Platte River Basin for two reasons. First, the flows and pollution of these tributaries are quite small. For example, the flow in one of the uncalibrated streams, Cherry Creek, is less than 20 cubic feet per second (cfs) and the dissolved oxygen is above 8 Mg/ℓ (this compares with an average flow on the South Platte River of over 300 cfs and a DO level of 7.0 Mg/ℓ). Second, the limited flow and quality data available to characterize these tributaries are generally sufficient.

The PIONEER-I model has the capability of modeling three water quality parameters in addition to the ones listed above - algae, zinc, and fecal coliform. Algae were not considered in the present calibration effort because of a complete lack of algal biomass measurements. It was evident during the calibration that some algal activity was present in Boulder Creek and the Cache la Poudre River because DO levels were consistently measured above saturation levels. Whether this

increase in DO was due to phytoplankton photosynthesis or to DO production from attached plants is not known. However, the lack of data precluded actual modeling of algae. Numerous zinc measurements were made in the basin but two factors prevented a meaningful calibration of zinc in the model: first, most of the measurements showed little or no zinc present in the water; secondly, no sources of zinc could be identified.

Considerable data were collected on fecal coliform in municipal and industrial effluents and in various rivers in the basin. An initial review of the data indicated that calibration of the PIONEER-I model on coliform should be possible, but in running the model it became apparent that there was little correlation between the effluent loadings of coliform and the instream measurements of coliform population. This lack of correlation is most likely due to the widely varying coliform concentrations measured in the waste effluents. For example, measurements at the Ft. Collins No. 2 municipal waste treatment plant show coliform levels varying from 10 to 670,000 MF count/100 ml.

Flow Input Data

The flow data used for the calibration period of August 1971 are shown in Table 6. Also shown in this table are the computed inflow and withdrawals calculated between each of the gauging stations using the detailed water balance technique discussed above.

Water Quality Input Data

One of the most important water quality parameters in the South Platte River Basin is dissolved oxygen (DO). In modeling DO, the following effects must be considered.

- BOD exertion
- Reaeration
- Photosynthesis and respiration
- Benthic demand exertion

The rate constants for BOD exertion can be obtained with reasonable accuracy from the measured data of BOD decay along the stretch of the river. The reaeration rate is controlled by a number of factors such as the velocity and depth of the river. Since no reaeration rate measurements in the South Platte River Basin have been made, a reaeration formula was determined by

TABLE 6

AVERAGE FLOW CONDITIONS FOR SOUTH PLATTE RIVER BASIN MODEL CALIBRATION, AUGUST 1971

ID* NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
SOUTH PLATTE RIVER				
33	Lake George Colo.	403.6	358.0	
				-144.0
1	Below Cheeseman Lake, Colo.	374.5	214.0	
				0.0
2	South Platte, Colo.	350.8	616.0	
				44.1
3	Waterton, Colo.	341.3	281.0	
				7.63
4	Littleton, Colo.	329.2	248.0	
5	Denver, Colo.	317.3	305.0	
				116.3
6	Henderson, Colo.	301.4	458.0	
				364.6
7	Kersey, Colo.	246.1	327.0	
8	Weldona, Colo.	206.7	385.0	
				205.6
9	Balzac, Colo.	173.9	281.0	
				224.3
10	Julesburg, Colo.	86.6	25.0	
31	Paxton, Nebr.**	33.5		
				141.7
32	North Platte, Nebr.	4.0	168.0	
NORTH FORK OF SOUTH PLATTE RIVER				
11	Grant, Colo.	39.0	291.0	
				88.0
12	South Platte, Colo.	0.3	0.5	

* The identification numbers correspond to those used in the system layout and data report.

** This station was discontinued.

ID NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
PLUM CREEK				
13	Plum Creek, Colo.	7.5		
BEAR CREEK				
14	Morrison, Colo.	10.8	37.3	
15	Sheridan, Colo.	1.3	23.0	
CHERRY CREEK				
16	Cherry Creek, Colo.	32.1	1.0	
CLEAR CREEK				
17	Clear Creek, Colo.	45.1	169.0	
18	Golden, Colo.	17.5	219.0	44.4
19	Derby, Colo.	0.6	23.8	
ST. VRAIN CREEK				
20	Lyons, Colo.	34.3	127.0	371.7
24	Platteview, Colo.	1.3	210.0	
BOULDER CREEK				
21	Orodell, Colo.	28.8	86.0	35.2
SOUTH BOULDER CREEK				
22	Eldorado Springs, Colo.	2.5	38.6	

ID NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
COAL CREEK				
23	Planview, Colo.	19.5	3.8	
BIG THOMPSON RIVER				
25	Drake, Colo.	37.6	96.6	
				334.4
26	LaSalle, Colo.	1.6	130.0	
CACHE LA POUDRE RIVER				
27	Ft. Collins, Colo.	56.3	217.0	
				612.1
28	Greeley, Colo.	3.0	66.6	
LODGEPOLE CREEK				
29	Ralton, Nebr.	8.3	4.0	
				-4.7
30	Bushnell, Nebr.	114.0	2.8	

regression analysis on data from other rivers. Although the results using this equation appear reasonable, the applicability of this formulation to this river basin should be investigated more thoroughly. In addition, since the water velocities and depths are not well defined in the basin, the actual calibrated values of reaeration may be a source of error in the DO model. The contribution of photosynthesis and respiration to the DO in the rivers was assumed to be zero. This assumption appeared valid for most stretches, with some exceptions (such as certain stretches along Boulder Creek).

The benthic oxygen demand was set at zero in most of the basin. (Although some benthic demand is generally present in unpolluted or slightly polluted streams it is very small. The benthic demand in these areas does not affect the general DO level in the stream to any significant degree when compared to the suspended BOD loading). Downstream of the large municipal and industrial effluents the benthic demand was adjusted to obtain the proper DO levels and profiles. Instream measurements indicated that considerable suspended material was present just below the outfalls and the amount of suspended material decreased as a function of distance below the outfall. Hence, the presence of significant oxygen consuming bottom sediments at these locations would be expected.

A significant portion of the flow in each river in the South Platte River Basin comes from undefined sources such as surface runoff and groundwater inflow. The water quality of this inflow is not known in most cases. During the calibration, reasonable values were assigned to this water for all of the important quality parameters.

The water quality data used for calibration were collected in August and September 1971.[10] The average was calculated for all of the data taken during these months at a given location for each parameter and the model was calibrated using these averaged values. Less weight was given to data points where only a single measurement was made.

Calibration Results

Listings of the input data and computed output for this calibration are shown in Appendix A. The results of the calibrated model and the data used in the calibration are shown in Figures 10-27. Inspection of these figures shows that the calibration on DO and BOD is quite accurate. Even though the variation in the values measured at each sampling location was relatively high for both DO and BOD, the averaged values match reasonably well. Greater agreement with the averaged data points could be obtained by adjusting certain parameters. However, given the variation in the measured data and the fact that certain parameters such as reaeration, sedimentation rate, and benthic demand were unknown, it was felt that a closer fit was in general not justified. The calculated profiles indicate that the proper mechanisms have been accounted for in the model.

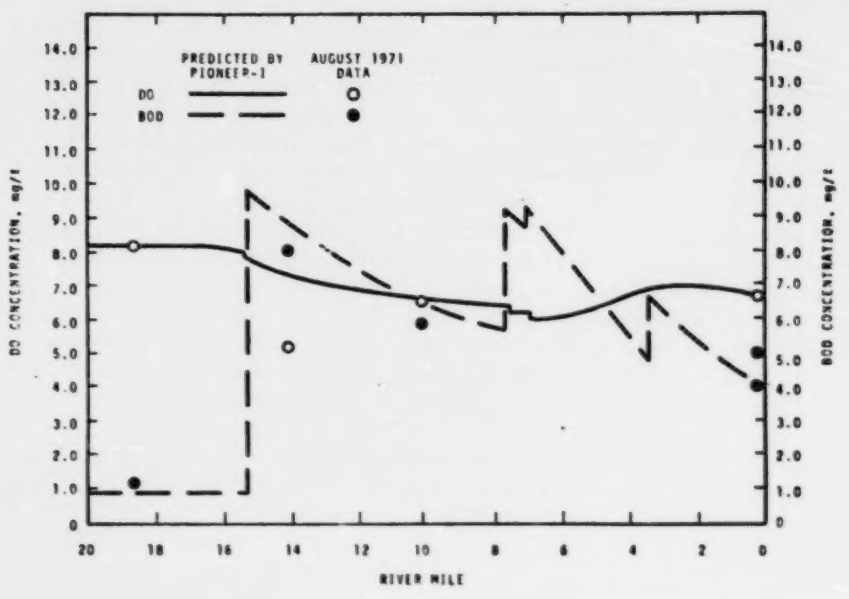


FIGURE 10. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON CLEAR CREEK FOR THE CALIBRATED PIONEER-I MODEL

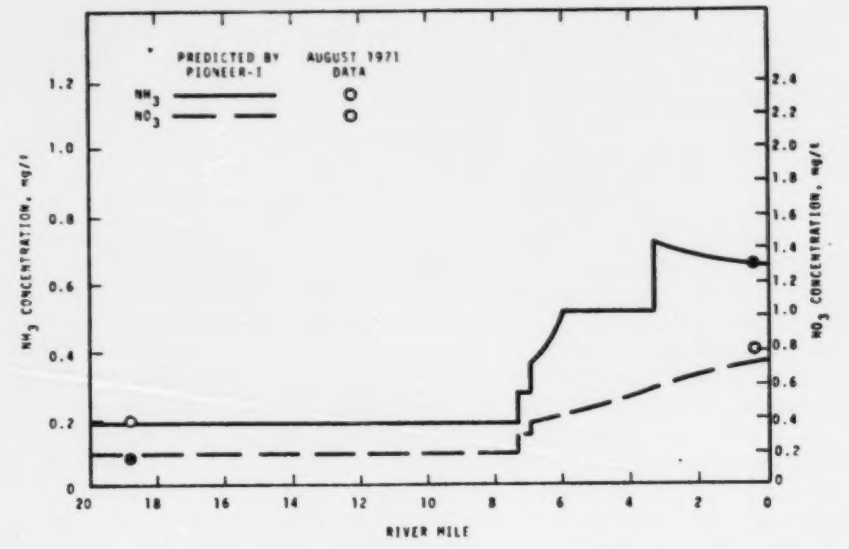


FIGURE 11. AMMONIA AND NITRATE PROFILES ON CLEAR CREEK FOR THE CALIBRATED PIONEER-I MODEL

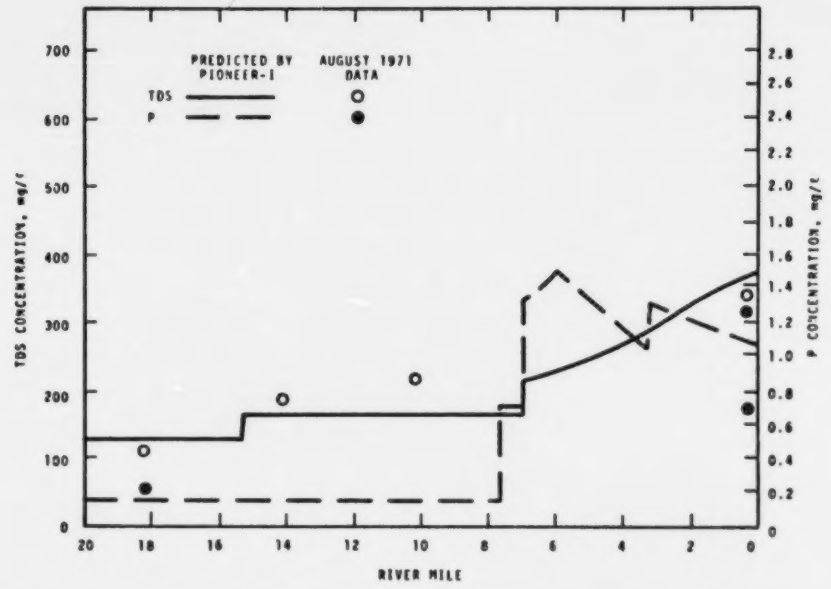


FIGURE 12. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON CLEAR CREEK FOR THE CALIBRATED PIONEER-I MODEL

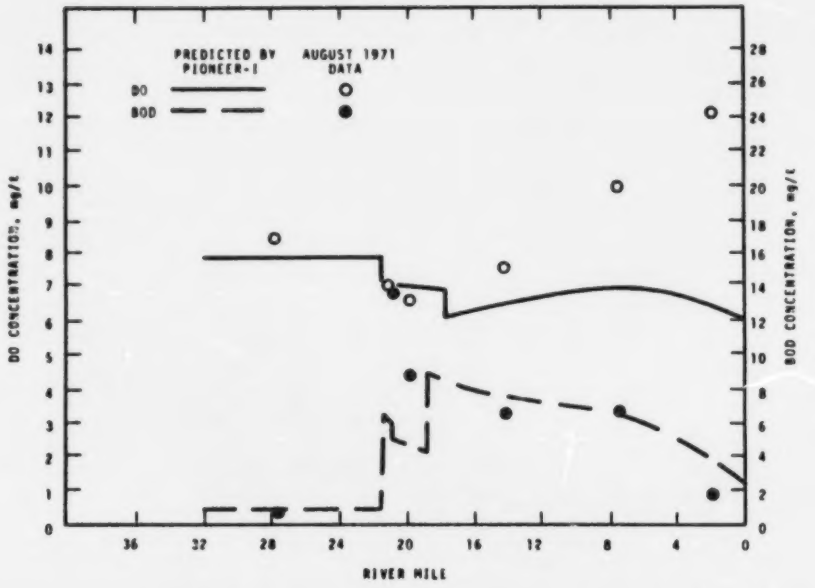


FIGURE 13. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND ON BOULDER CREEK FOR THE CALIBRATED PIONEER-I MODEL

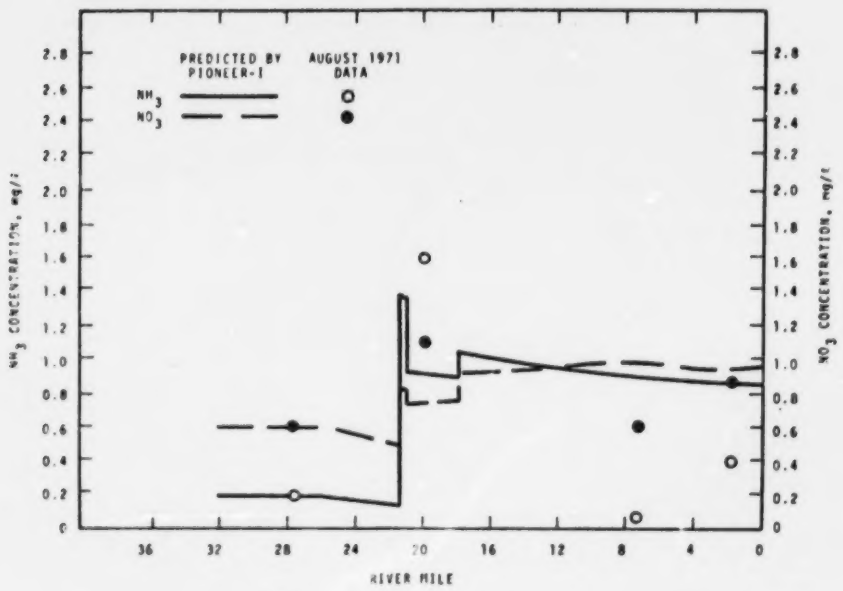


FIGURE 14. AMMONIA AND NITRATE PROFILES ON BOULDER CREEK FOR THE CALIBRATED PIONEER-I MODEL

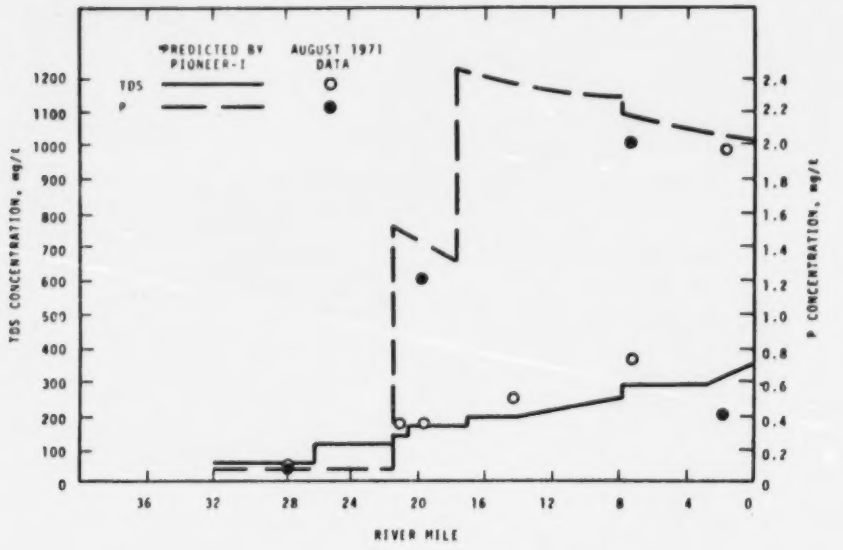


FIGURE 15. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON BOULDER CREEK FOR THE CALIBRATED PIONEER-I MODEL

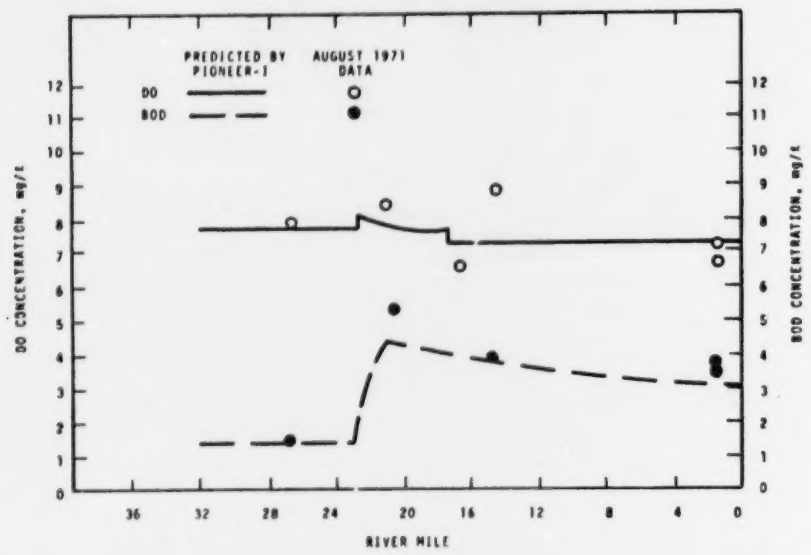


FIGURE 16. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON ST. VRAIN CREEK FOR THE CALIBRATED PIONEER-I MODEL

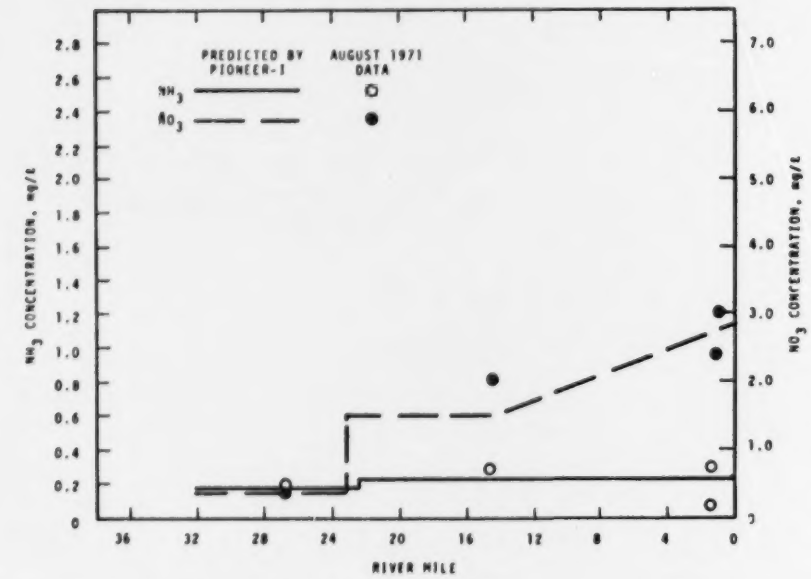


FIGURE 17. AMMONIA AND NITRATE PROFILES ON ST. VRAIN CREEK FOR THE CALIBRATED PIONEER-I MODEL

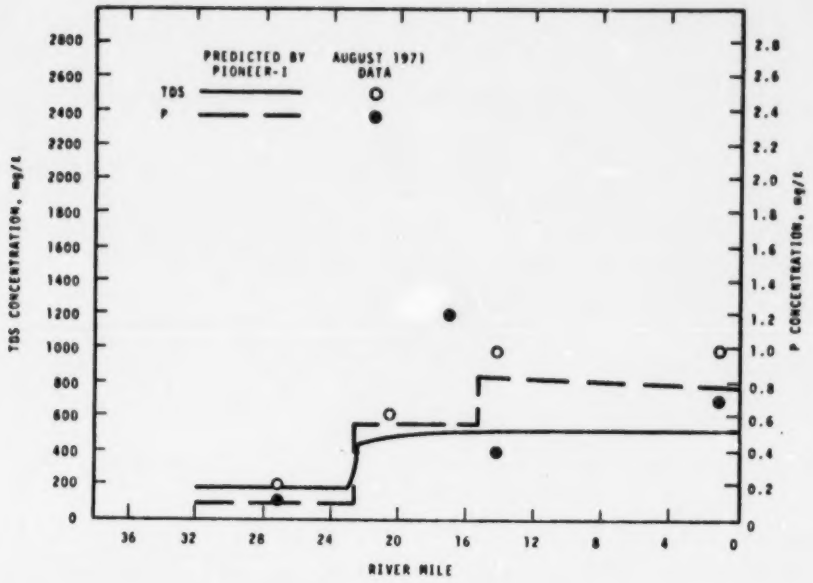


FIGURE 18. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON ST. VRAIN CREEK FOR THE CALIBRATED PIONEER-I MODEL

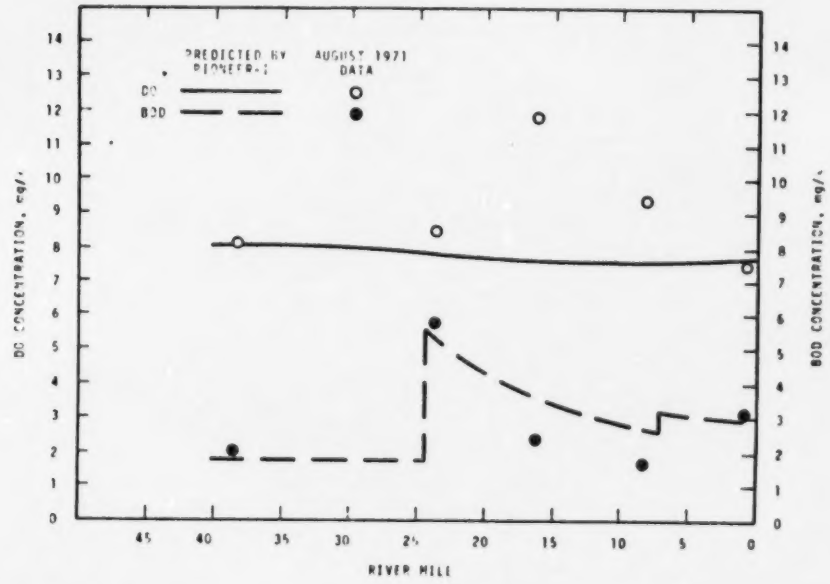


FIGURE 19. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND ON THE BIG THOMPSON RIVER FOR THE CALIBRATED PIONEER-I MODEL

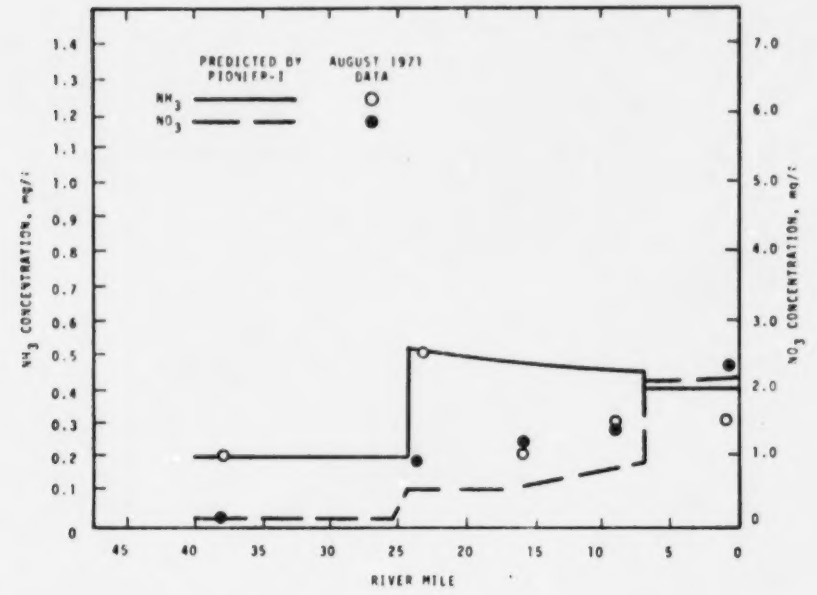


FIGURE 20. AMMONIA AND NITRATE RIVER MILE PROFILES ON THE BIG THOMPSON RIVER FOR THE CALIBRATED PIONEER-I MODEL

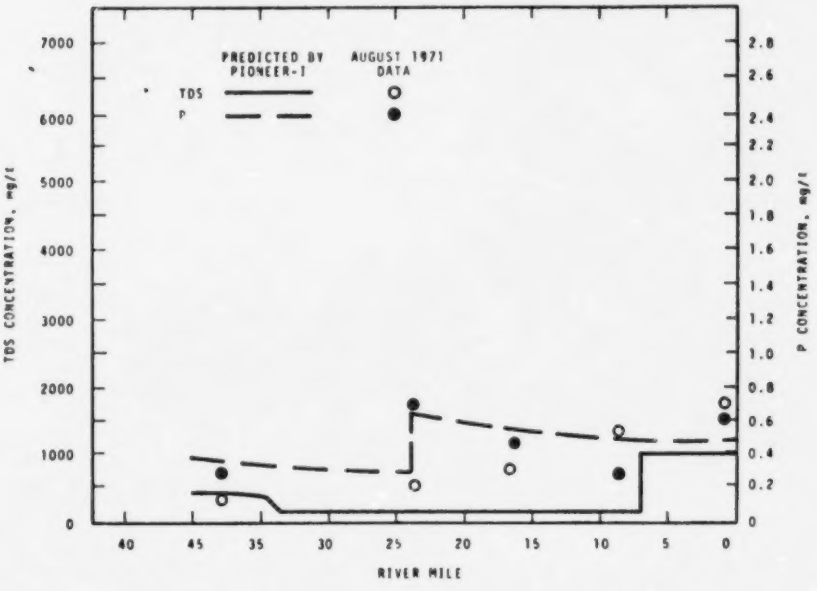


FIGURE 21. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON THE BIG THOMPSON RIVER FOR THE CALIBRATED PIONEER-I MODEL

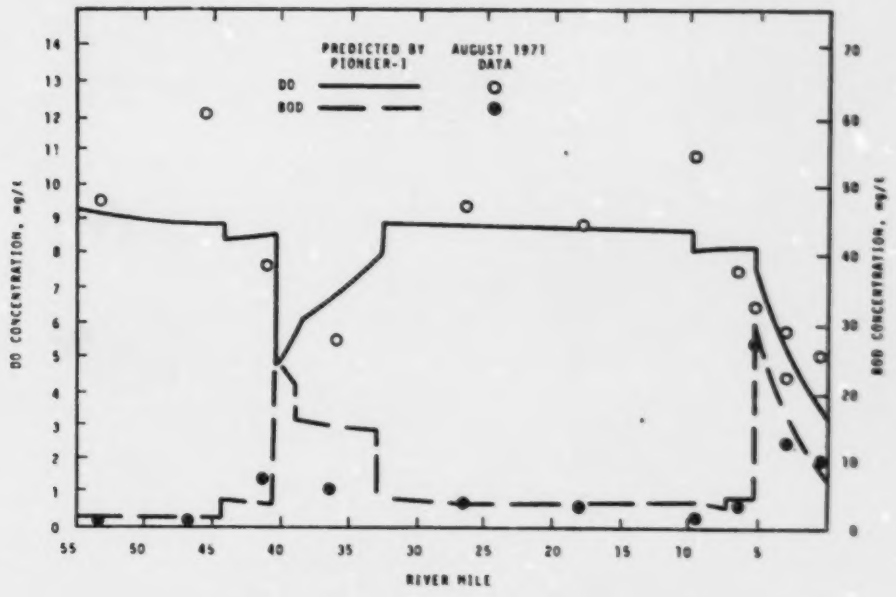


FIGURE 22. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON THE CACHE LA POUDRE RIVER FOR THE CALIBRATED PIONEER-I MODEL

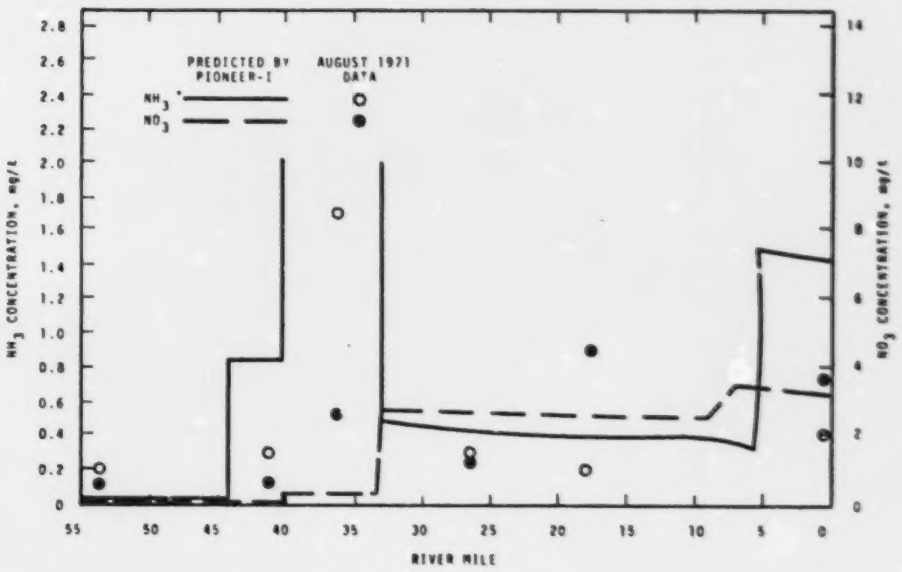


FIGURE 23. AMMONIA AND NITRATE RIVER MILE PROFILES ON THE CACHE LA POUDRE RIVER FOR THE CALIBRATED PIONEER-I MODEL

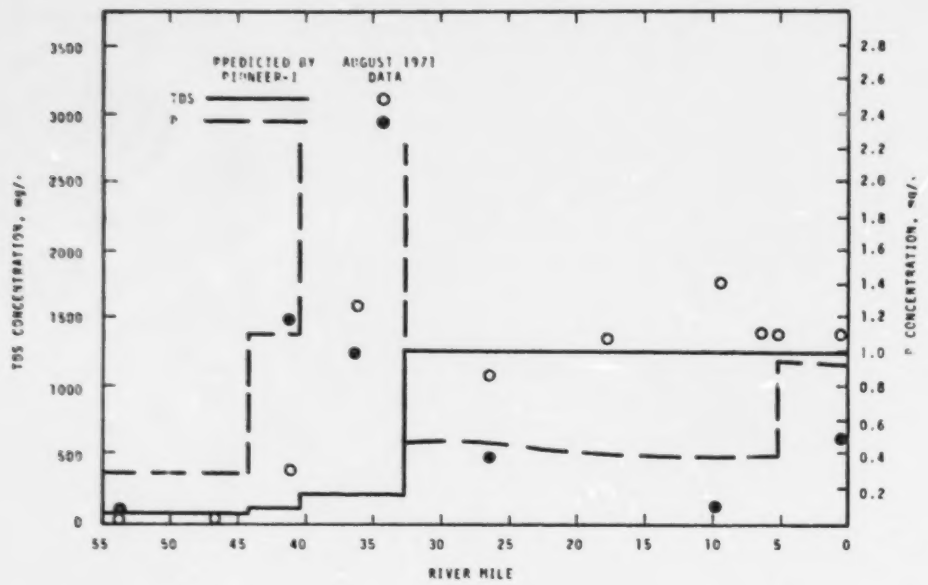


FIGURE 24. TOTAL DISSOLVED SOLIDS AND RIVER MILE PHOSPHORUS PROFILES ON THE CACHE LA POUDRE RIVER FOR THE CALIBRATED PIONEER-I MODEL

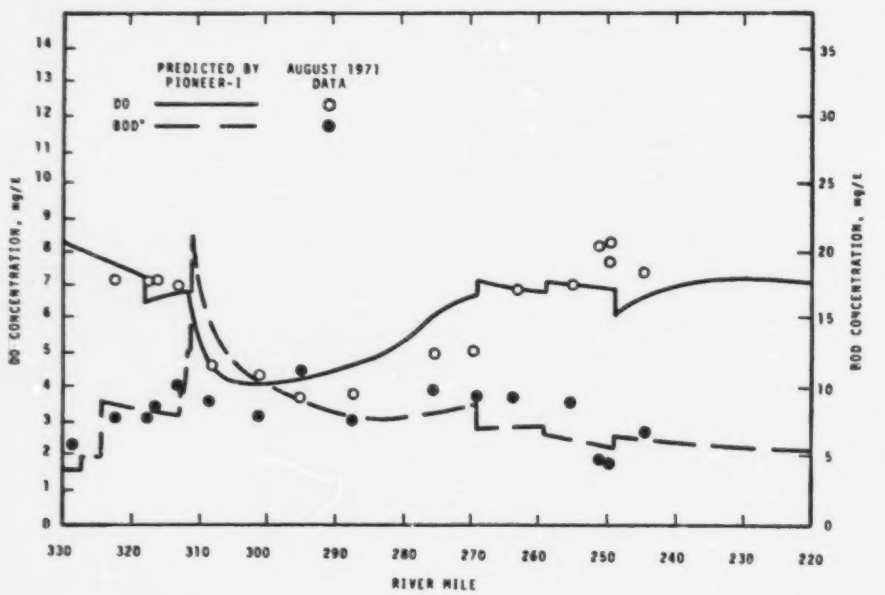


FIGURE 25. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON THE SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

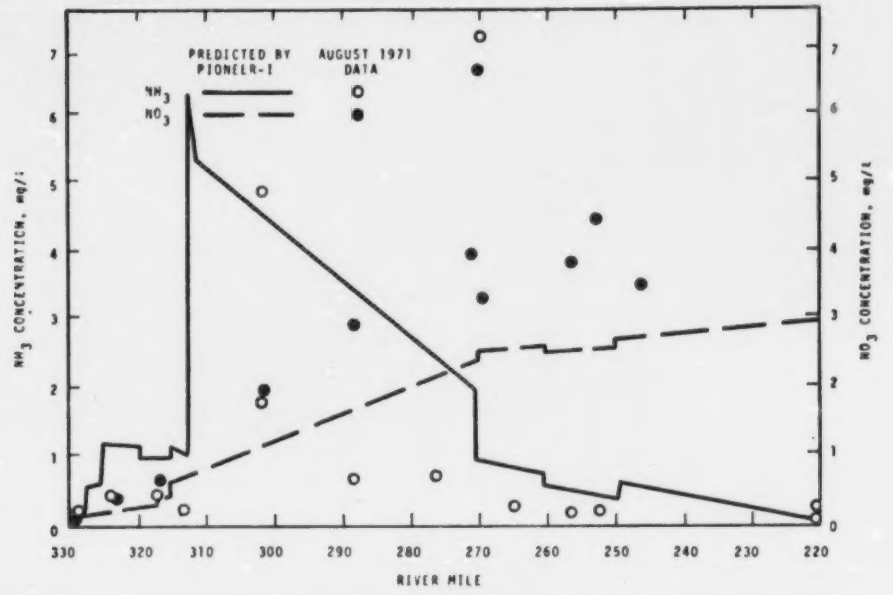


FIGURE 26. AMMONIA AND NITRATE PROFILES ON THE SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

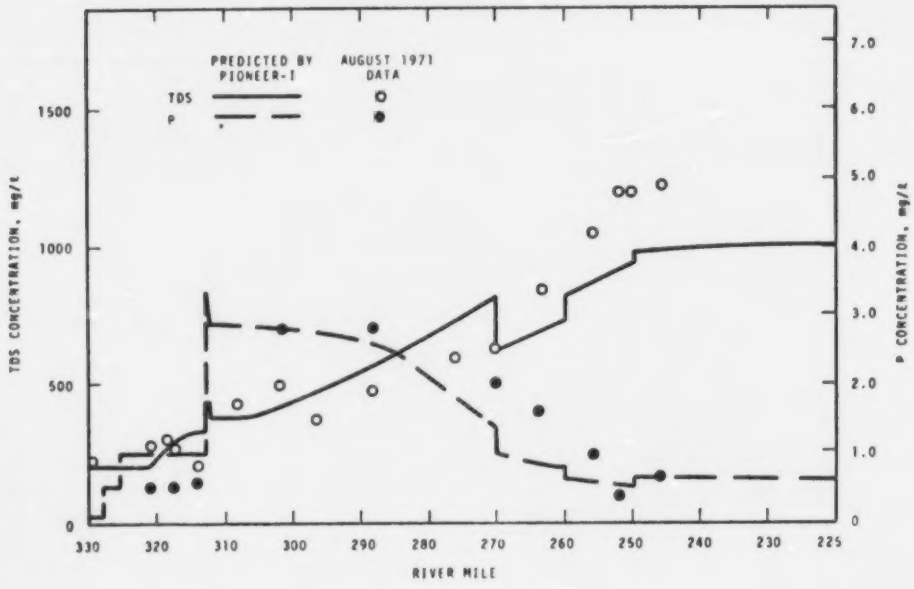


FIGURE 27. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON THE SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

Small ammonia concentrations were predicted reliably, but when large quantities of ammonia were present the model calculated concentrations far in excess of those measured. This occurred below all of the major municipal waste treatment plants in the basin. The rapid decay of ammonia concentration below these sources cannot be explained by biological processes such as nitrification or uptake by living organisms nor by physical processes such as ammonia loss to the atmosphere. In all cases, these processes are far slower than the measured decrease in ammonia concentrations would indicate. Since the nitrate concentrations are directly related to the ammonia concentrations and the behavior of the ammonia could not be explained satisfactorily, little effort was spent calibrating the nitrate model. It was evident however that considerable nitrate was entering the rivers in the unmeasured inflows.

The total dissolved solids and phosphorus profiles calculated for each river are in relatively good agreement with the measured data.

Results on Uncalibrated Reaches

Although the PIONEER-I model was not calibrated in the usual sense on a number of streams in the basin, full advantage was taken of all known data to simulate reasonable profiles on these streams. The results of these simulations are shown in Figures 28-56. In general, the profiles are reasonable and indicate the concentration levels to be expected for the water quality parameters of interest on each stretch of river. An effort was made to insure that the concentration levels at the mouth of each stream matched measured data, if available. When data were not available the profile was checked to insure that the concentrations predicted were reasonable considering the location of the stream and the type and size of pollution sources present. In all cases it was possible to match reasonably closely the measured or expected concentration levels using accepted values for model rate constants and inflowing concentrations.

CALIBRATION FOR THE WINTER PERIOD

The PIONEER-I model was set up and calibrated for winter conditions. This period contrasts with the summer period by having relatively low river flows and temperatures and large point waste sources not present during the summer. Because of these large differences it was necessary to recalibrate the model. The best water quality data for calibration of the model was taken during November and December of 1971.[10] During this period a relatively complete set of data was obtained over a large portion of

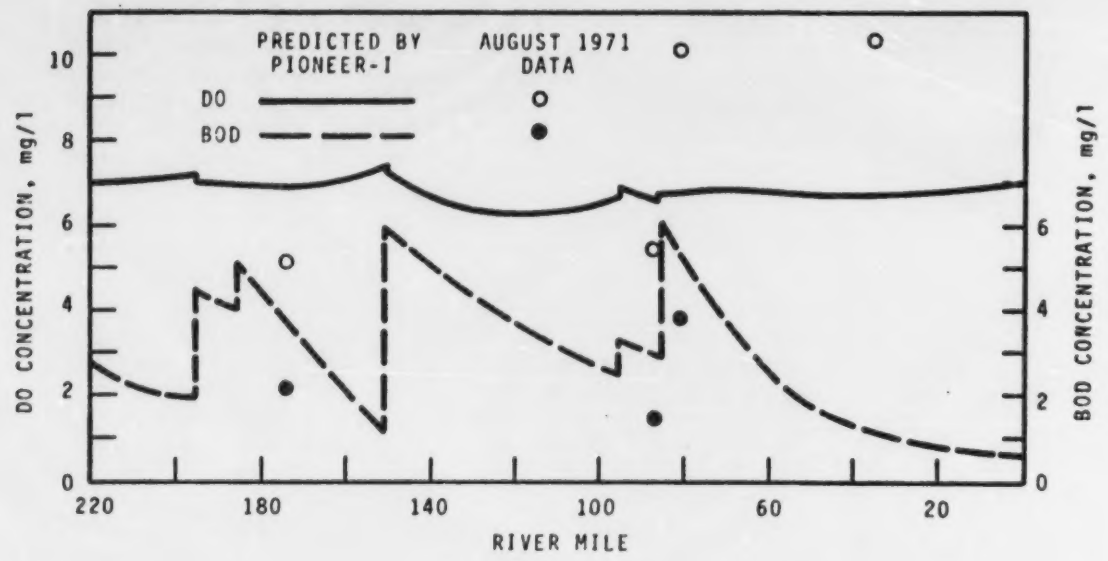


FIGURE 28. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON THE SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

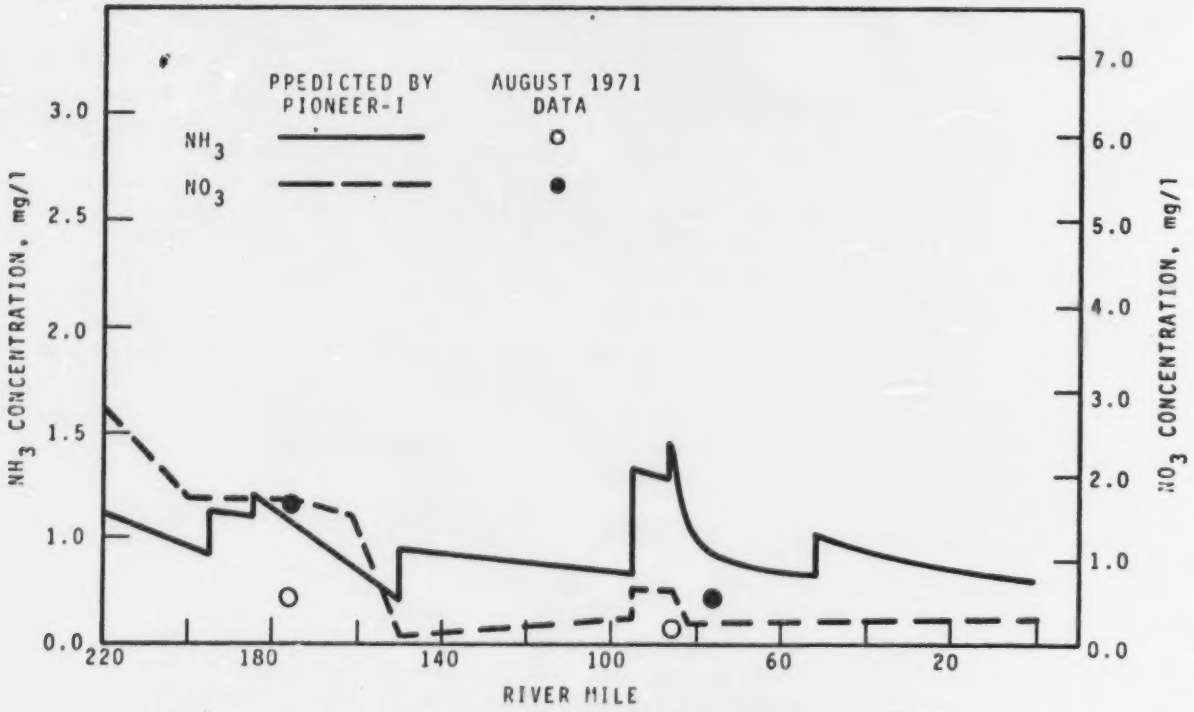


FIGURE 29. AMMONIA AND NITRATE PROFILES ON THE SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

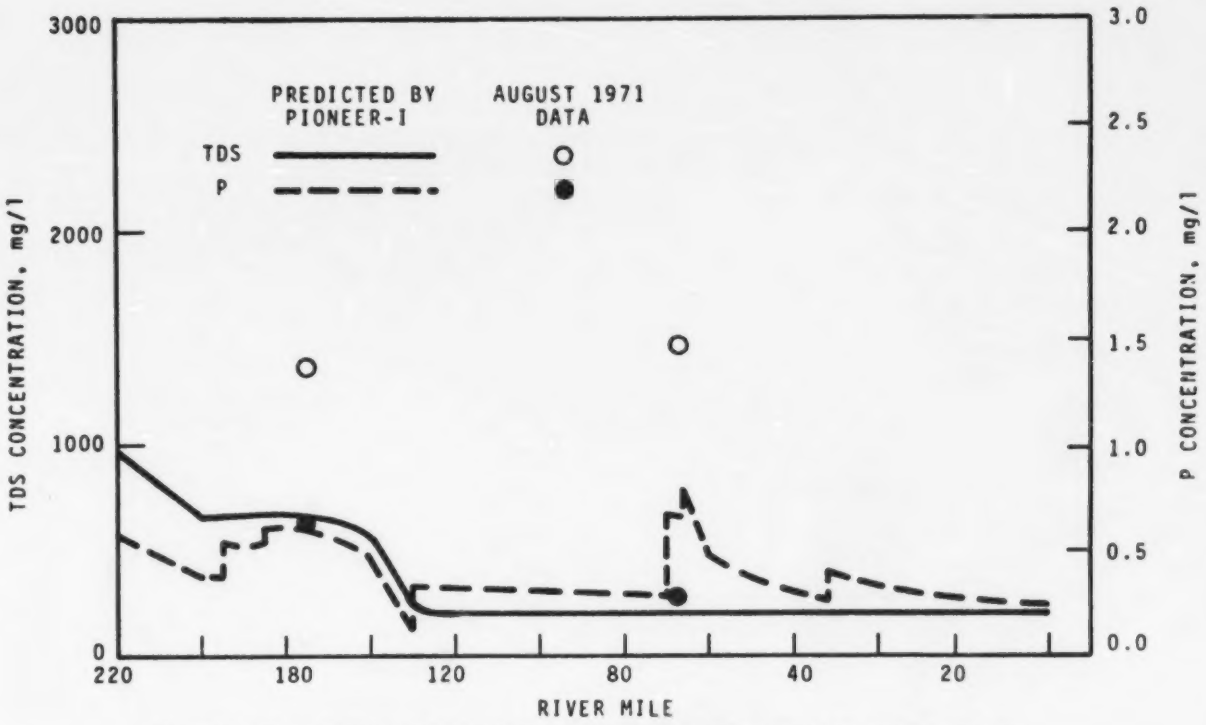


FIGURE 30. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON THE SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

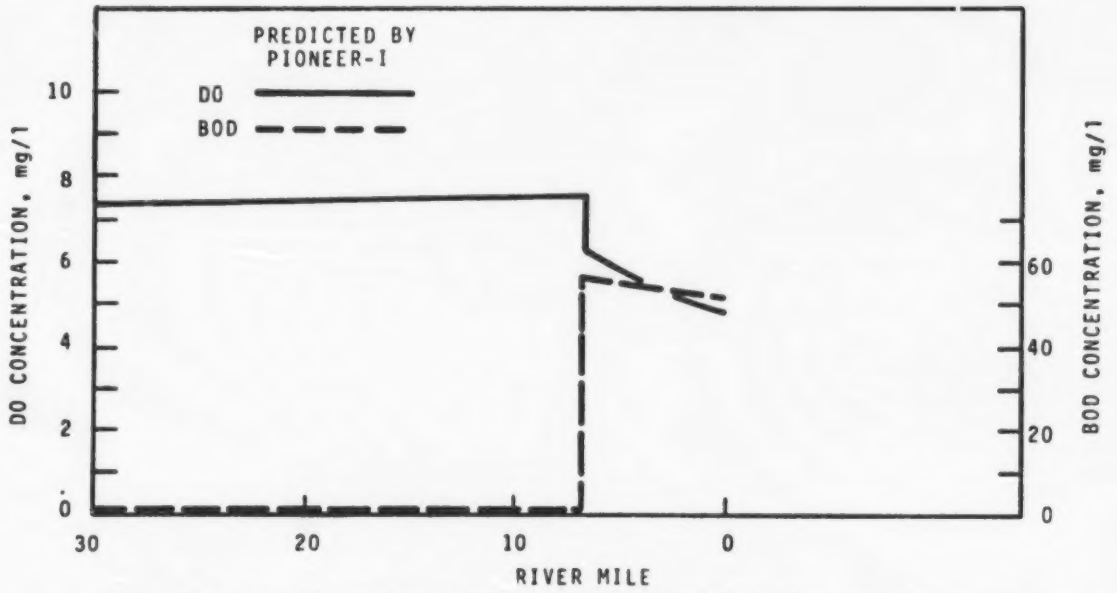


FIGURE 31. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON PLUM CREEK FOR THE CALIBRATED PIONEER-I MODEL

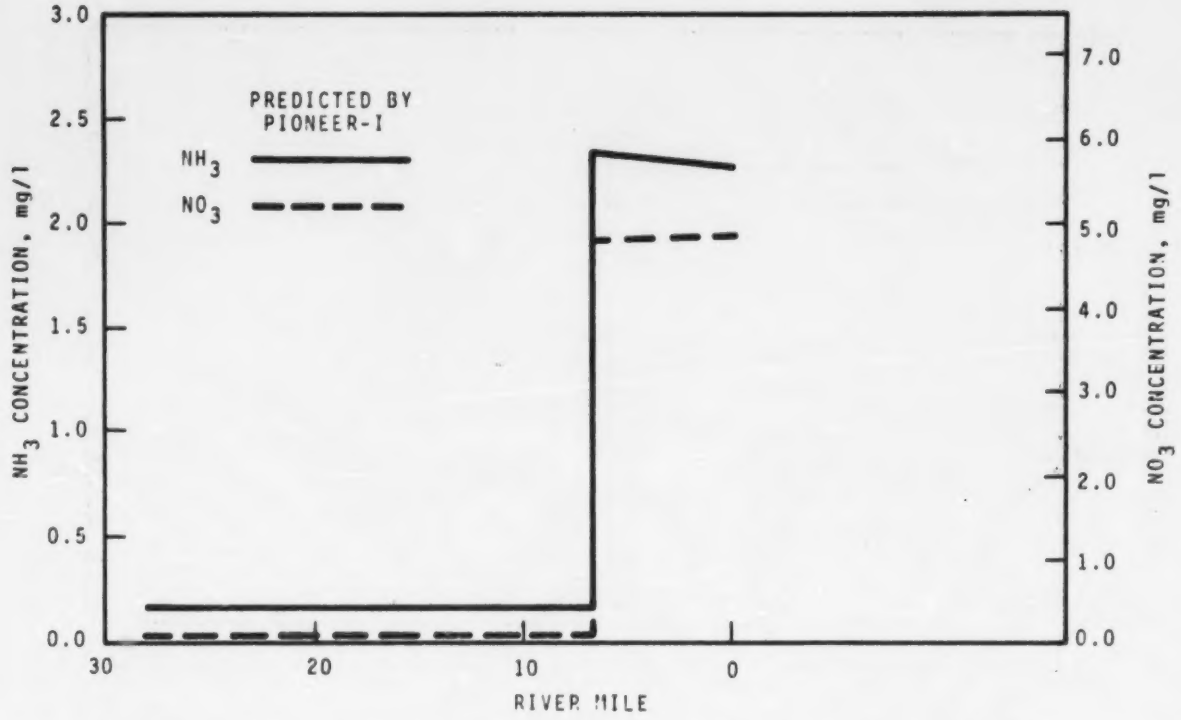


FIGURE 32. AMMONIA AND NITRATE PROFILES ON PLUM CREEK FOR THE CALIBRATED PIONEER-I MODEL

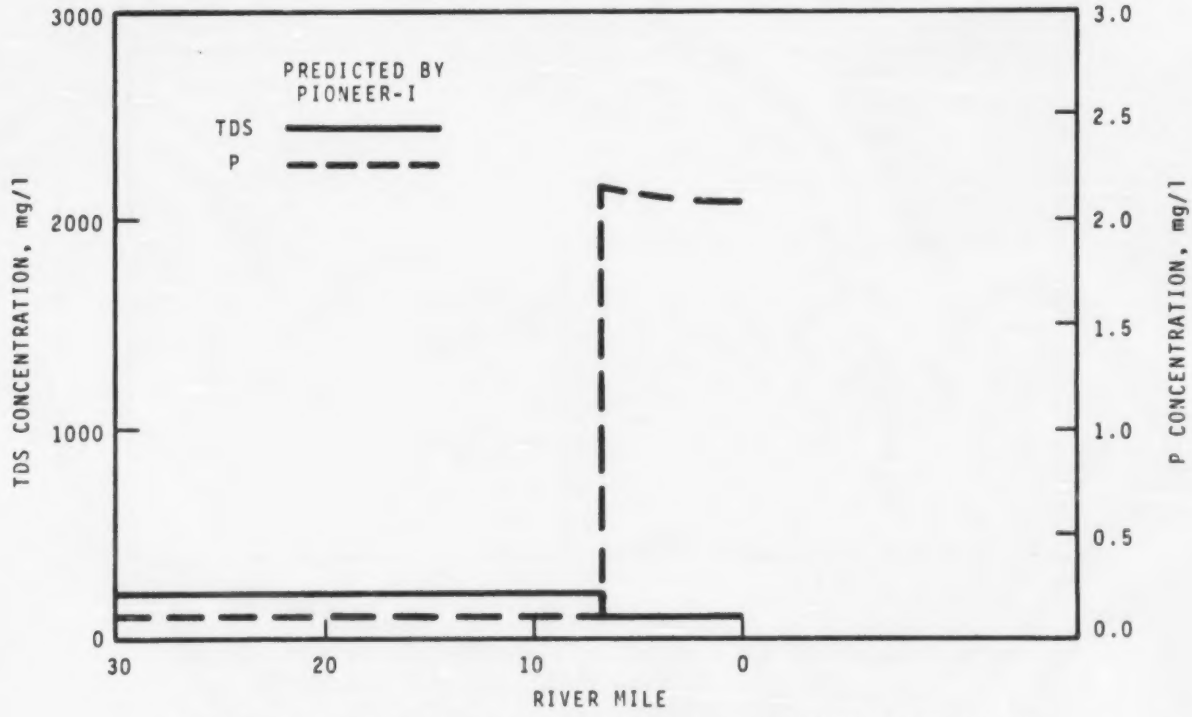


FIGURE 33. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON PLUM CREEK FOR THE CALIBRATED PIONEER-I MODEL

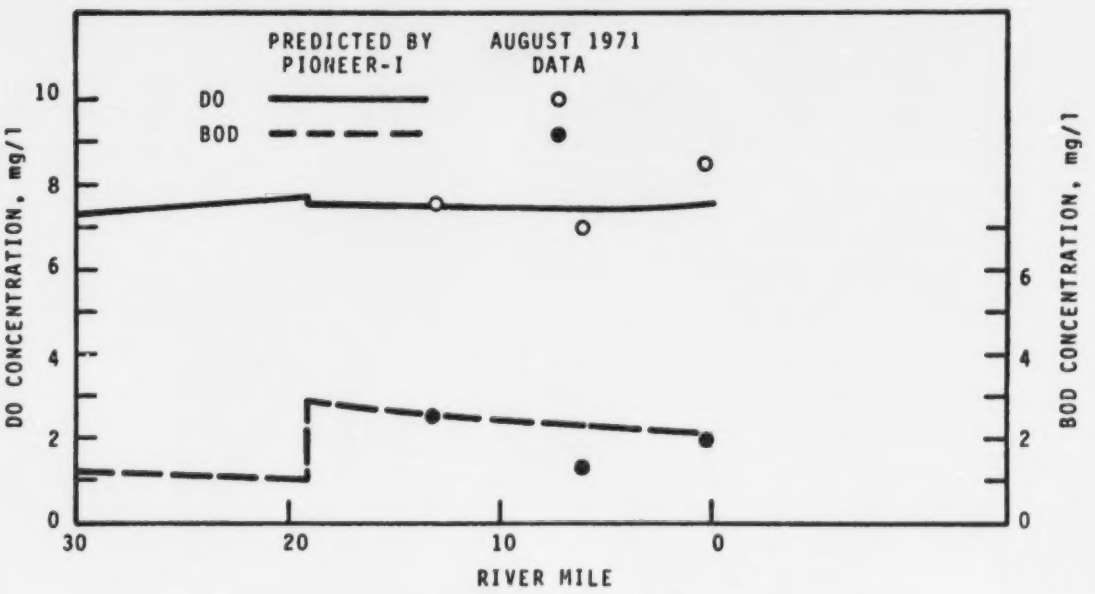


FIGURE 34. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON BEAR CREEK FOR THE CALIBRATED PIONEER-I MODEL

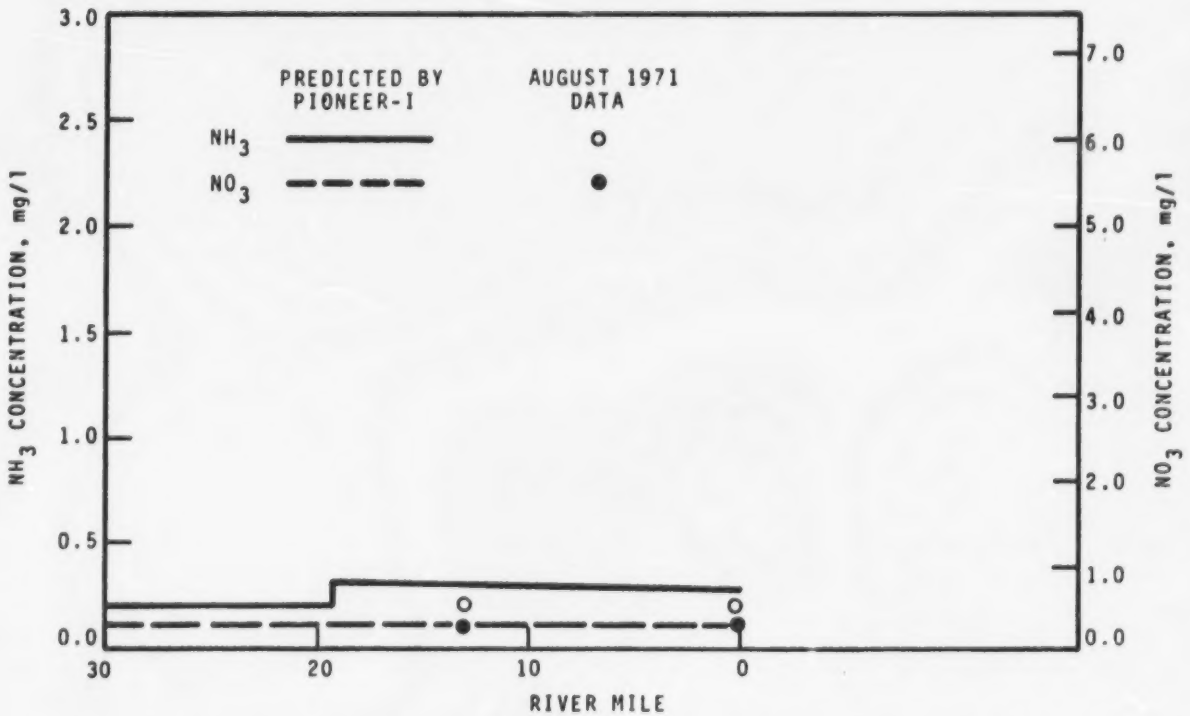


FIGURE 35. AMMONIA AND NITRATE PROFILES ON BEAR CREEK FOR THE CALIBRATED PIONEER-I MODEL

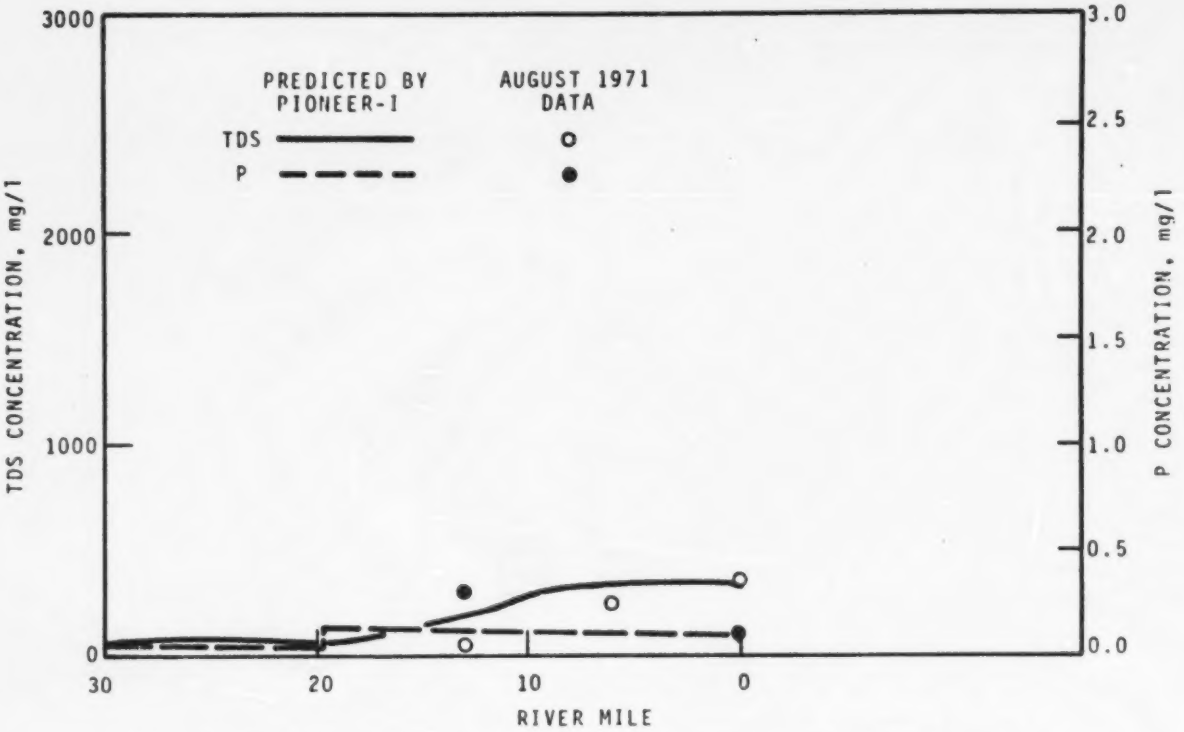


FIGURE 36. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON BEAR CREEK FOR THE CALIBRATED PIONEER-I MODEL

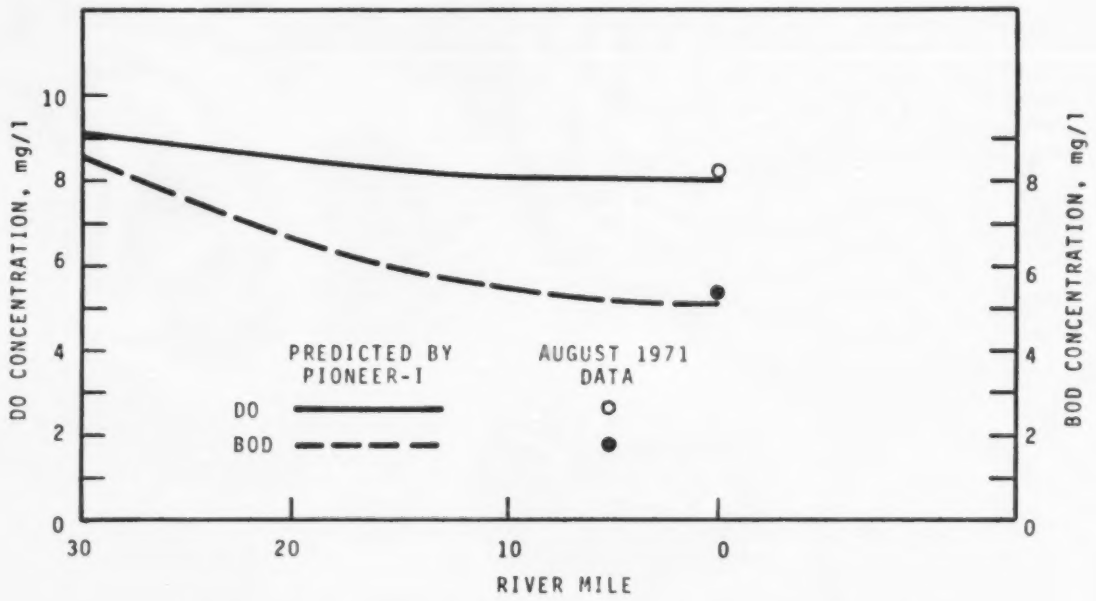


FIGURE 37. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON CHERRY CREEK FOR THE CALIBRATED PIONEER-I MODEL

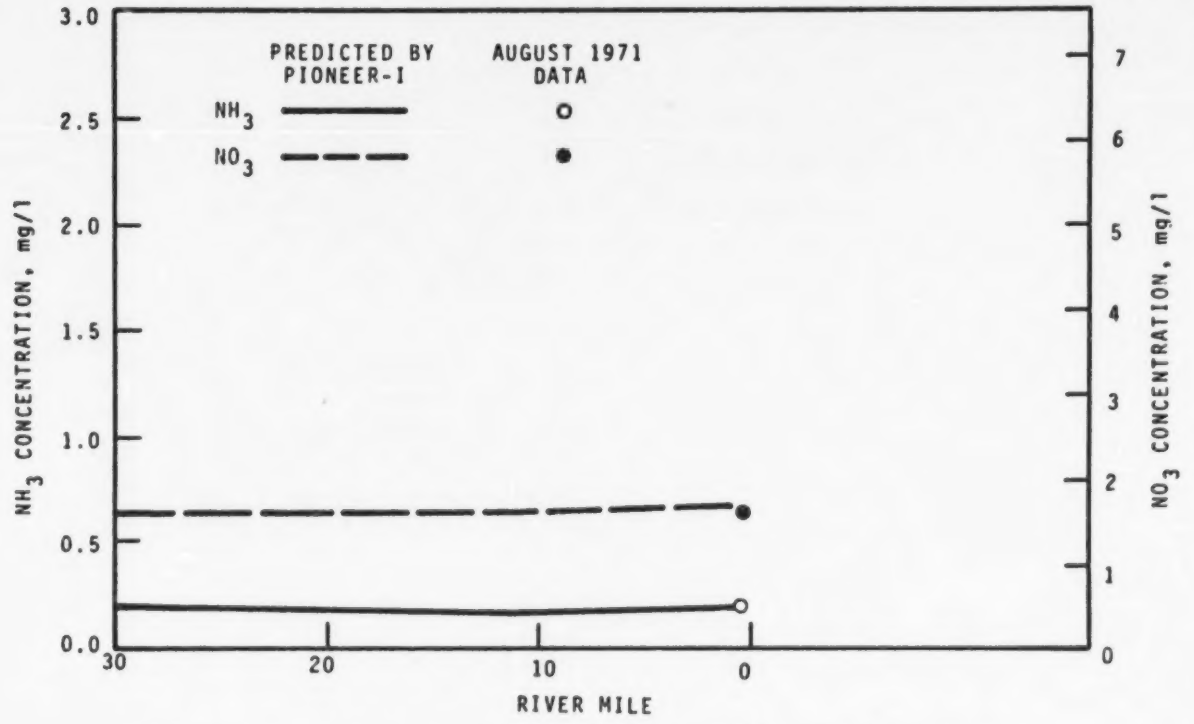


FIGURE 38. AMMONIA AND NITRATE PROFILES ON CHERRY CREEK FOR THE CALIBRATED PIONEER-I MODEL

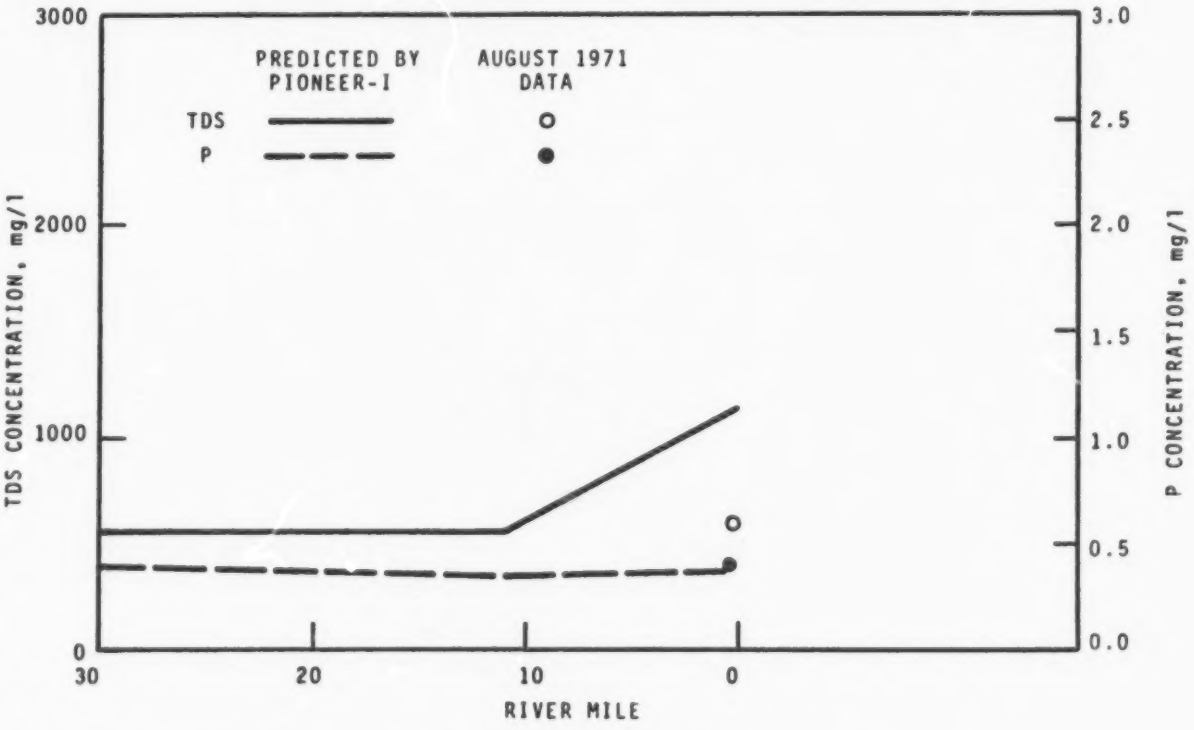


FIGURE 39. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON CHERRY CREEK FOR THE CALIBRATED PIONEER-I MODEL

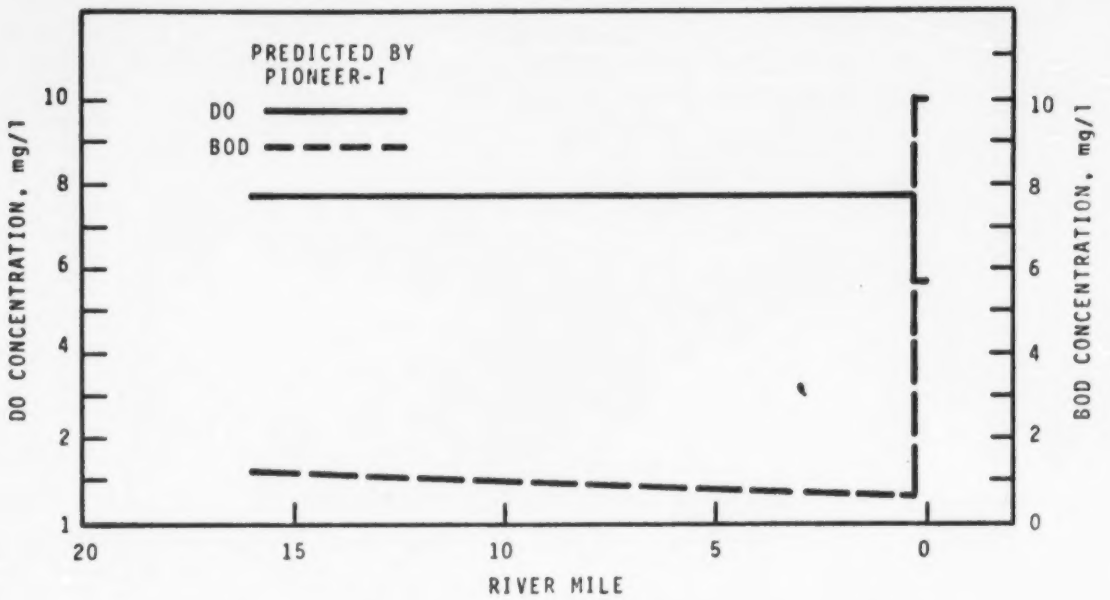


FIGURE 40. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON RALSTON CREEK FOR THE CALIBRATED PIONEER-I MODEL

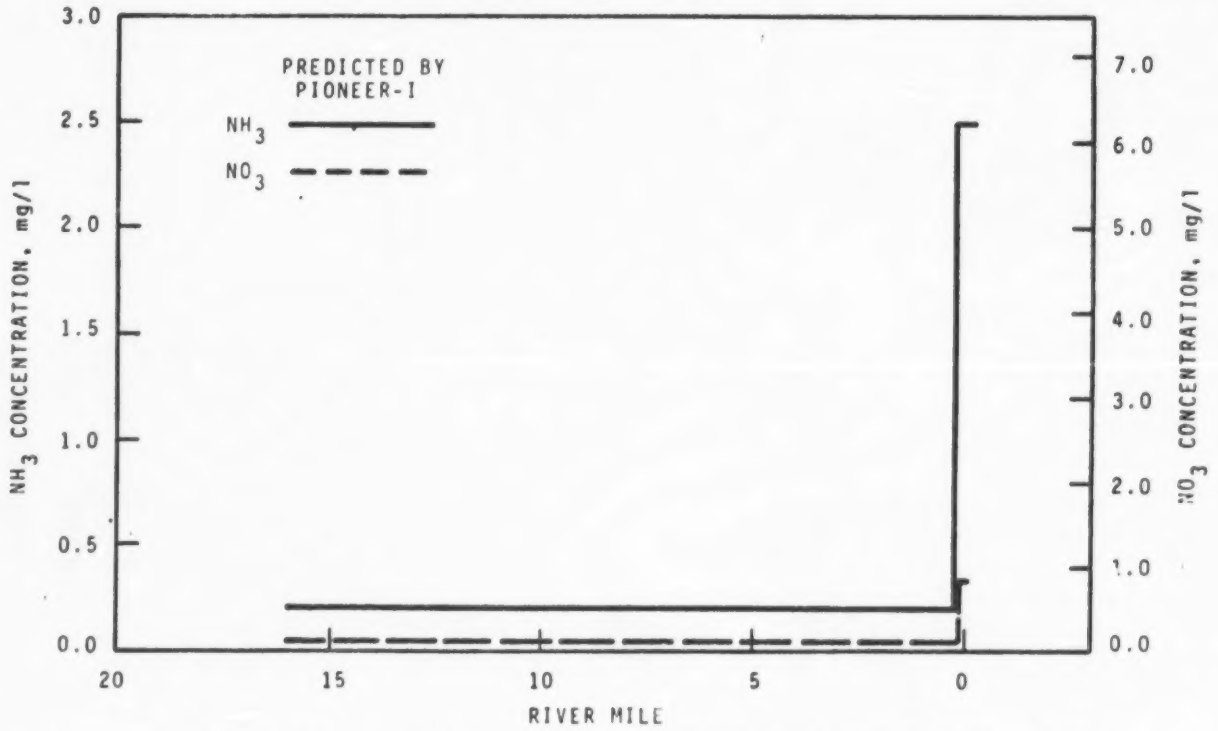


FIGURE 41. AMMONIA AND NITRATE PROFILES ON RALSTON CREEK FOR THE CALIBRATED PIONEER-I MODEL

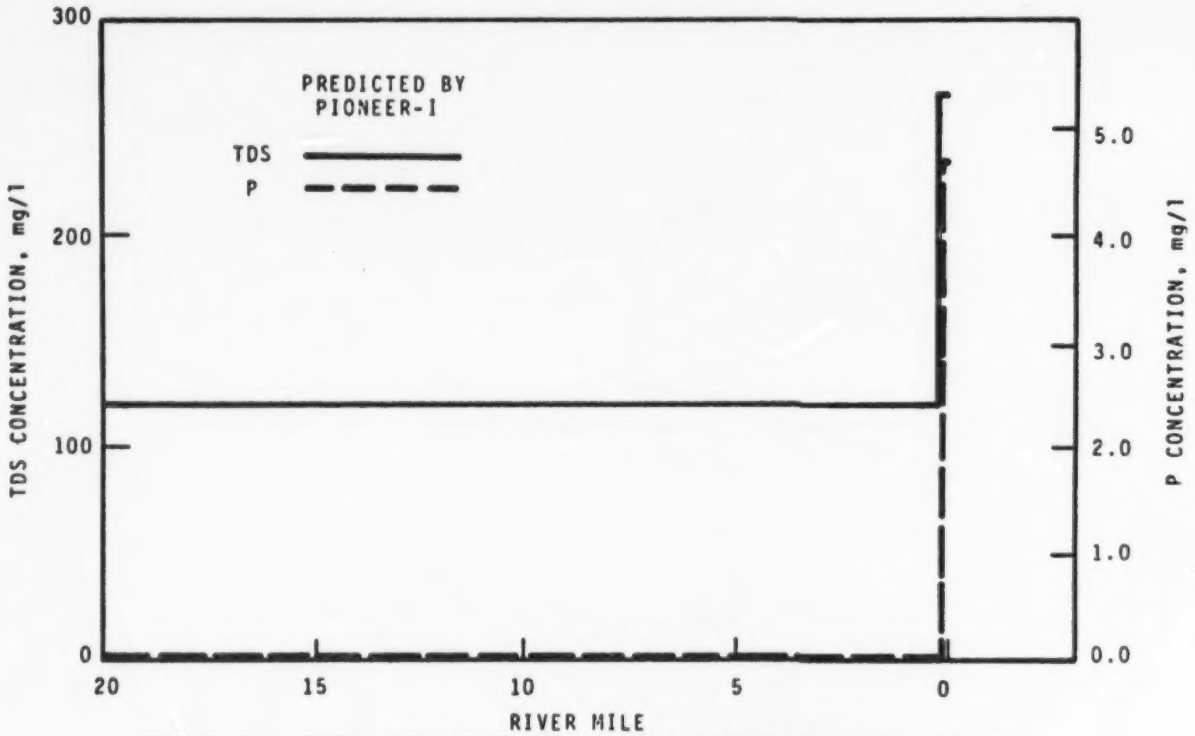


FIGURE 42. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON RALSTON CREEK FOR THE CALIBRATED PIONEER-I MODEL

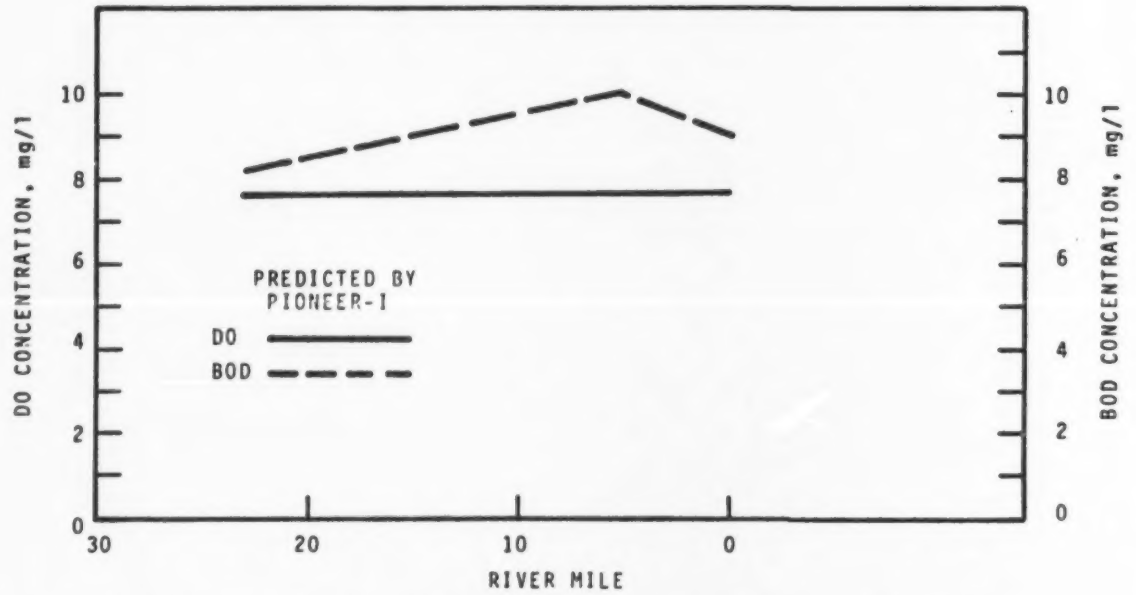


FIGURE 43. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON BIG DRY CREEK FOR THE CALIBRATED PIONEER-I MODEL

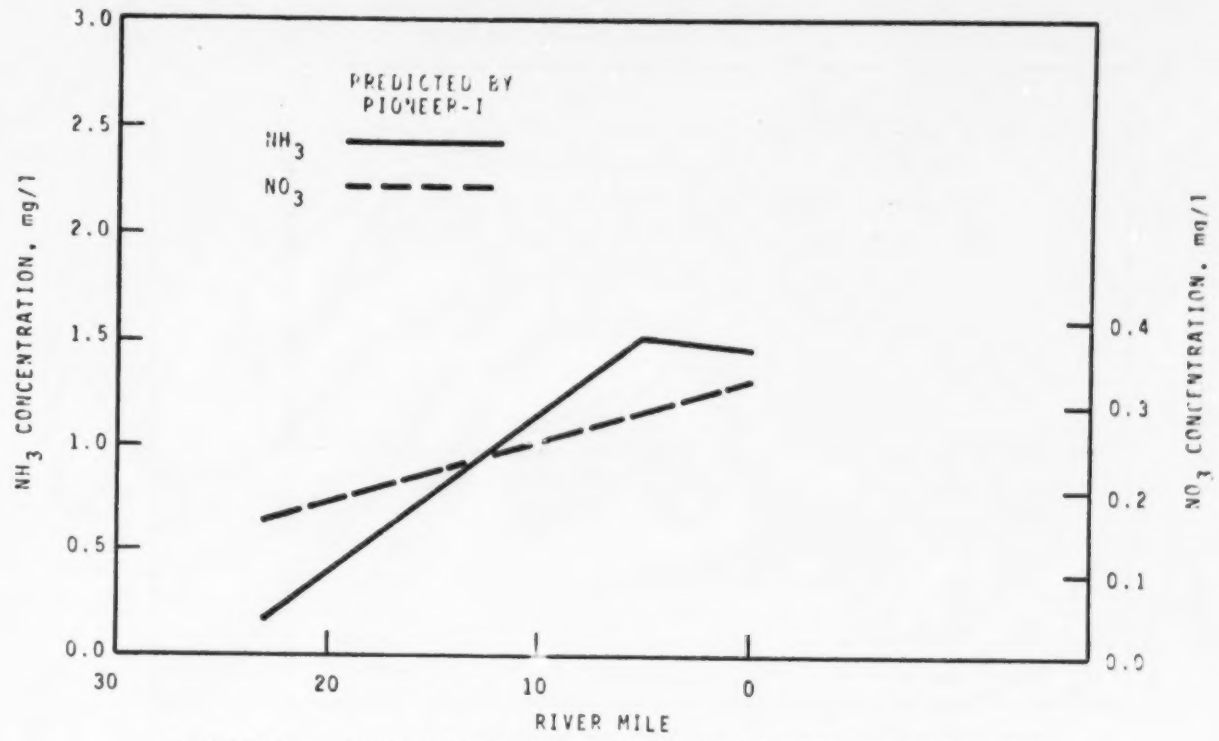


FIGURE 44. AMMONIA AND NITRATE PROFILES ON BIG DRY CREEK FOR THE CALIBRATED PIONEER-I MODEL

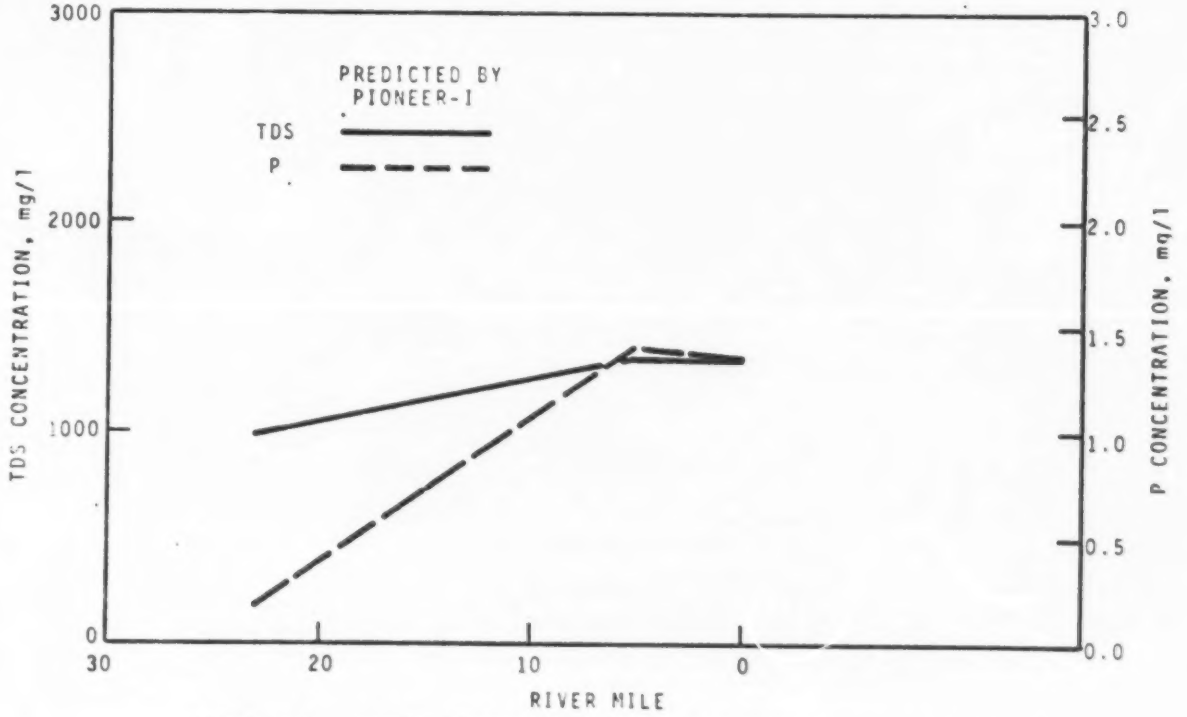


FIGURE 45. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON BIG DRY CREEK FOR THE CALIBRATED PIONEER-I MODEL

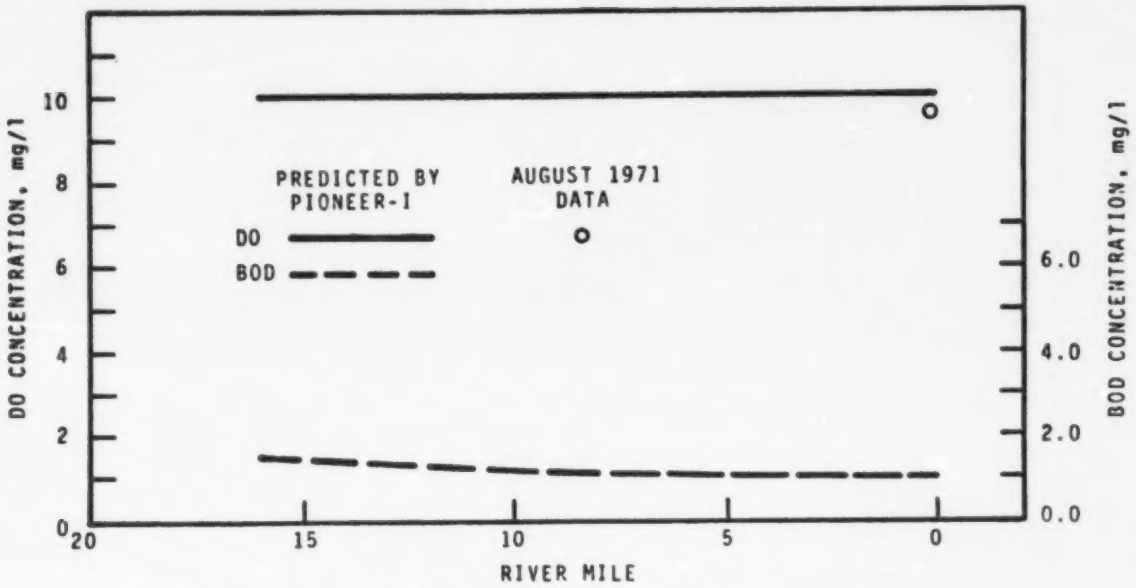


FIGURE 46. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON LEFTHAND CREEK FOR THE CALIBRATED PIONEER-I MODEL

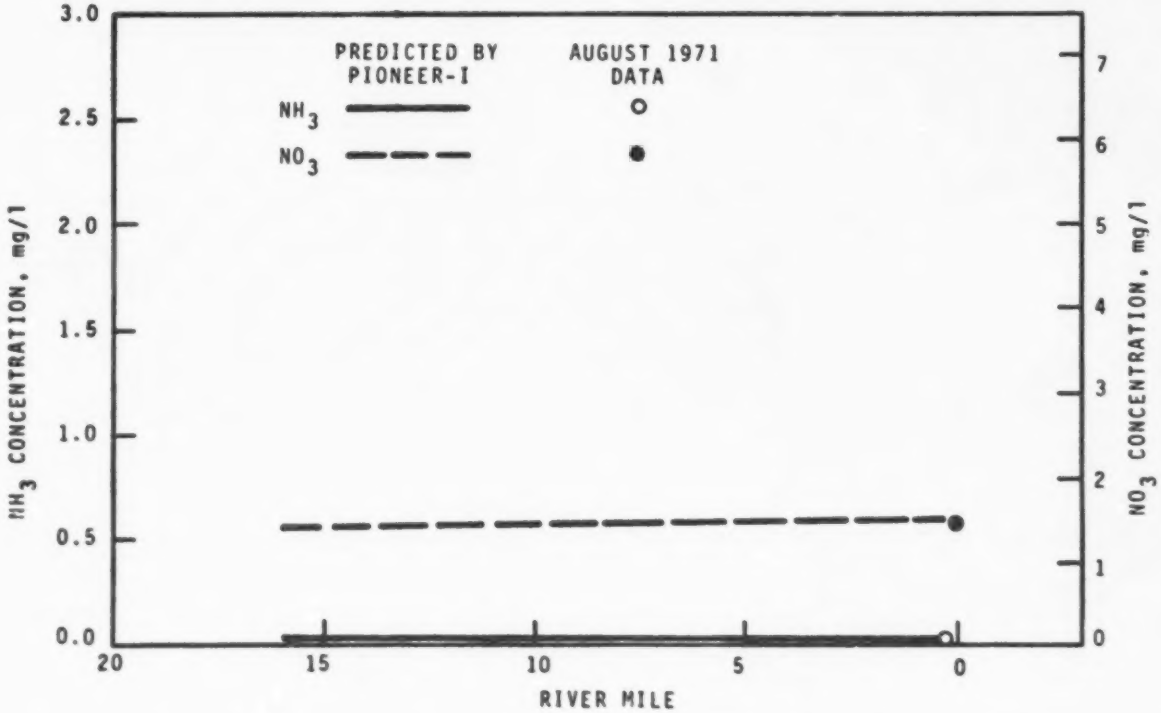


FIGURE 47. AMMONIA AND NITRATE PROFILES ON LEFTHAND CREEK FOR THE CALIBRATED PIONEER-I MODEL

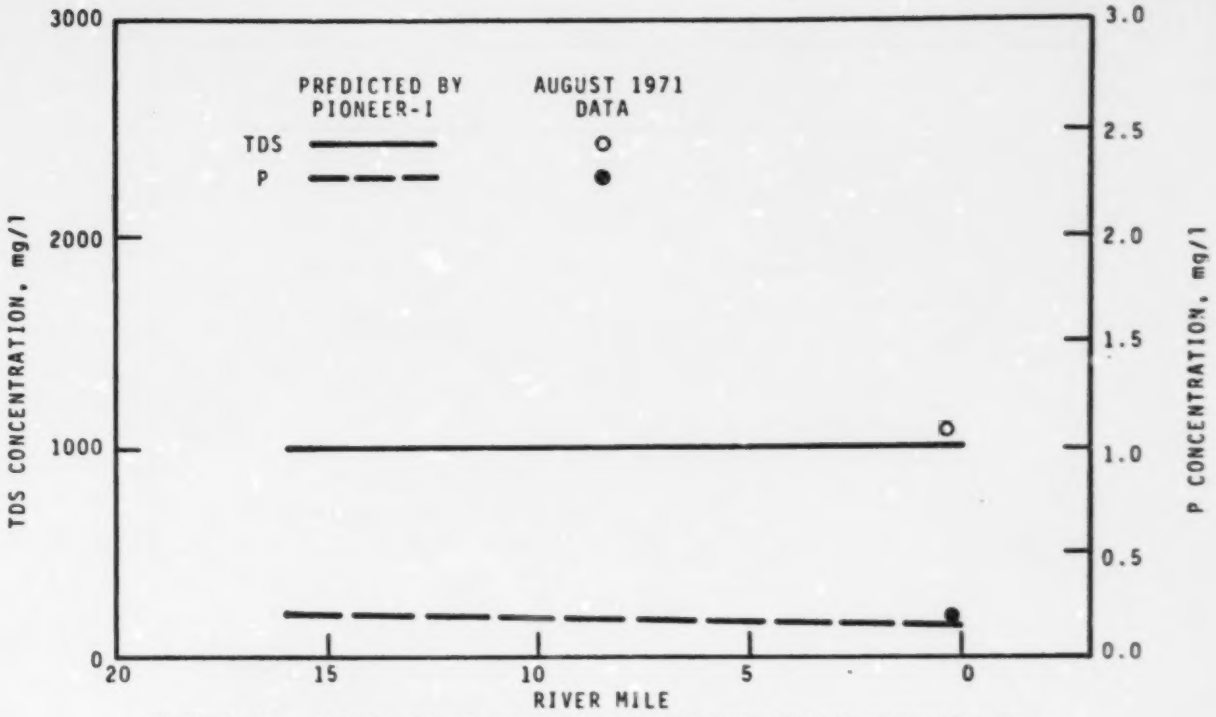


FIGURE 48. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON LEFTHAND CREEK FOR THE CALIBRATED PIONEER-I MODEL

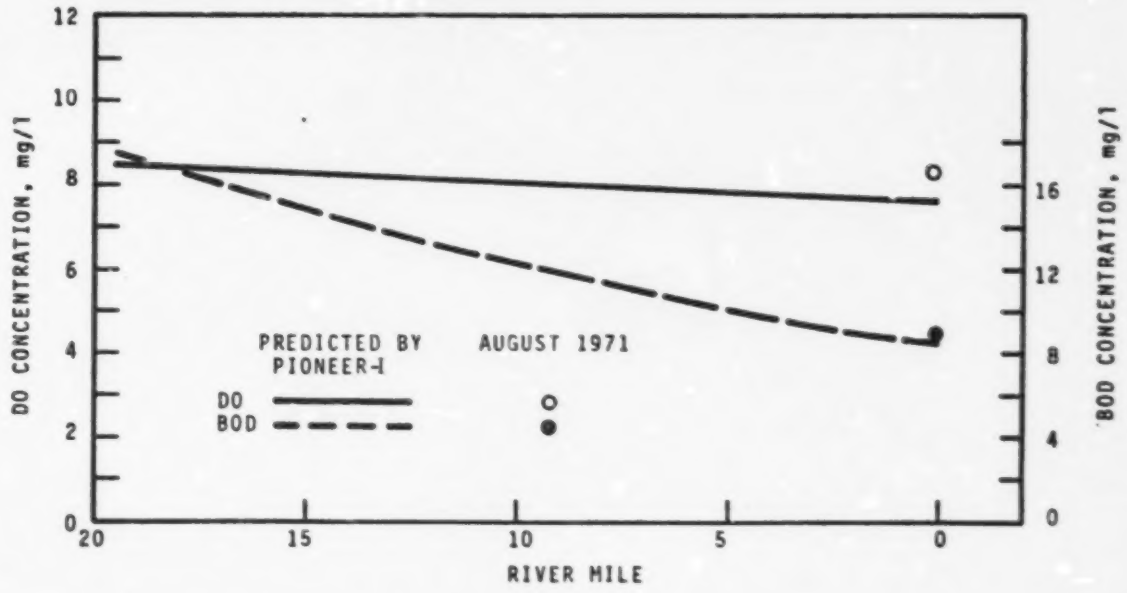


FIGURE 49. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON COAL CREEK FOR THE CALIBRATED PIONEER-I MODEL

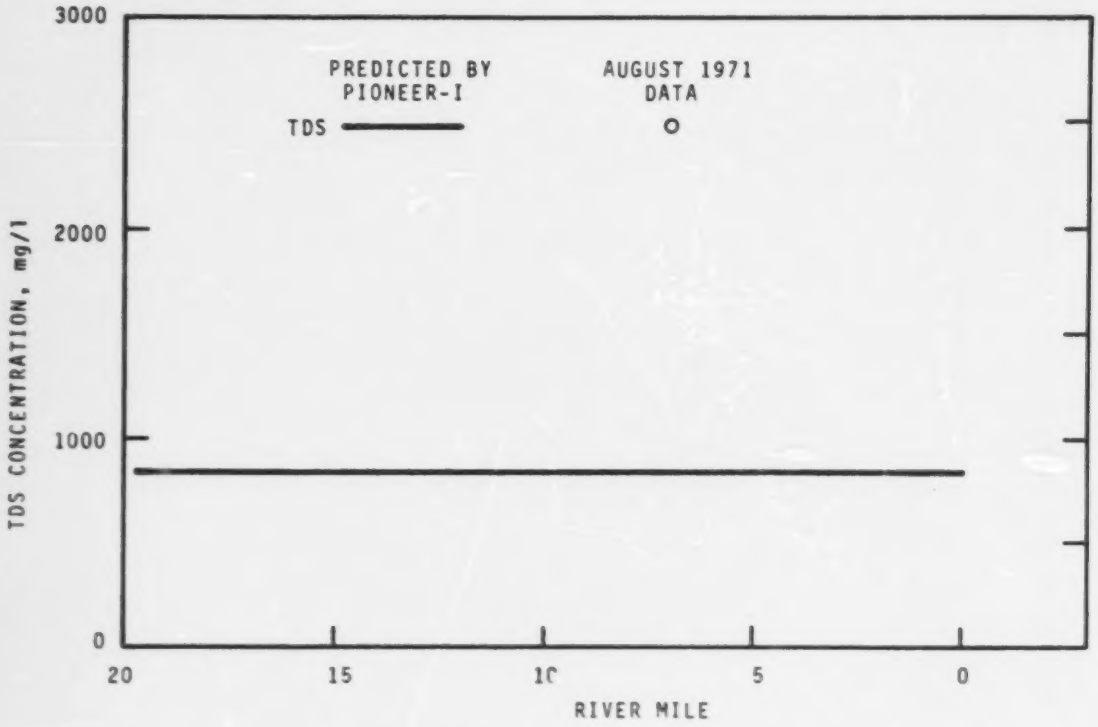


FIGURE 50. TOTAL DISSOLVED SOLIDS PROFILE ON COAL CREEK FOR THE CALIBRATED PIONEER-I MODEL

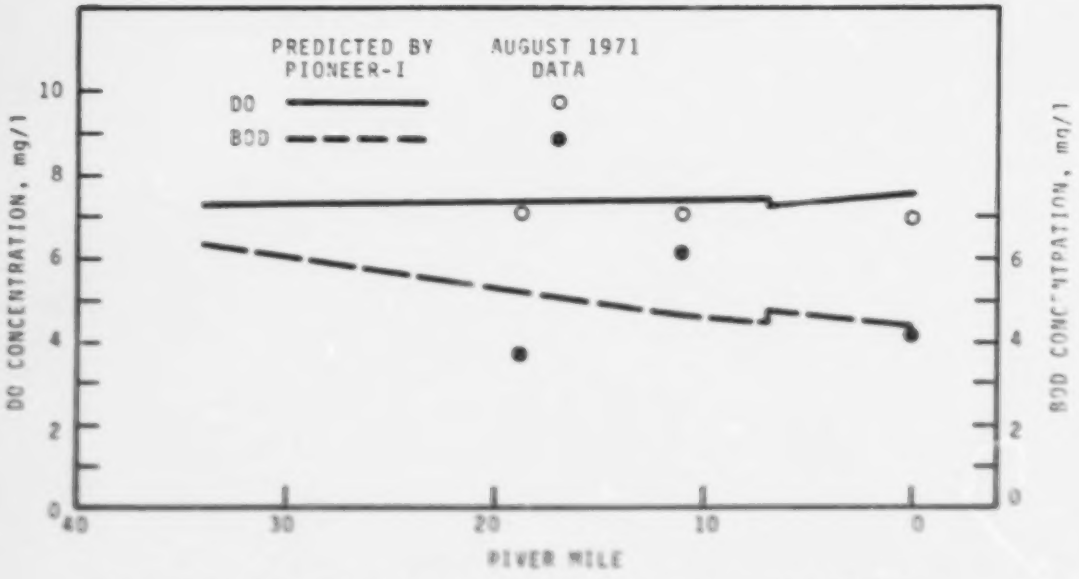


FIGURE 51. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON THE LITTLE THOMPSON RIVER FOR THE CALIBRATED PIONEER-I MODEL

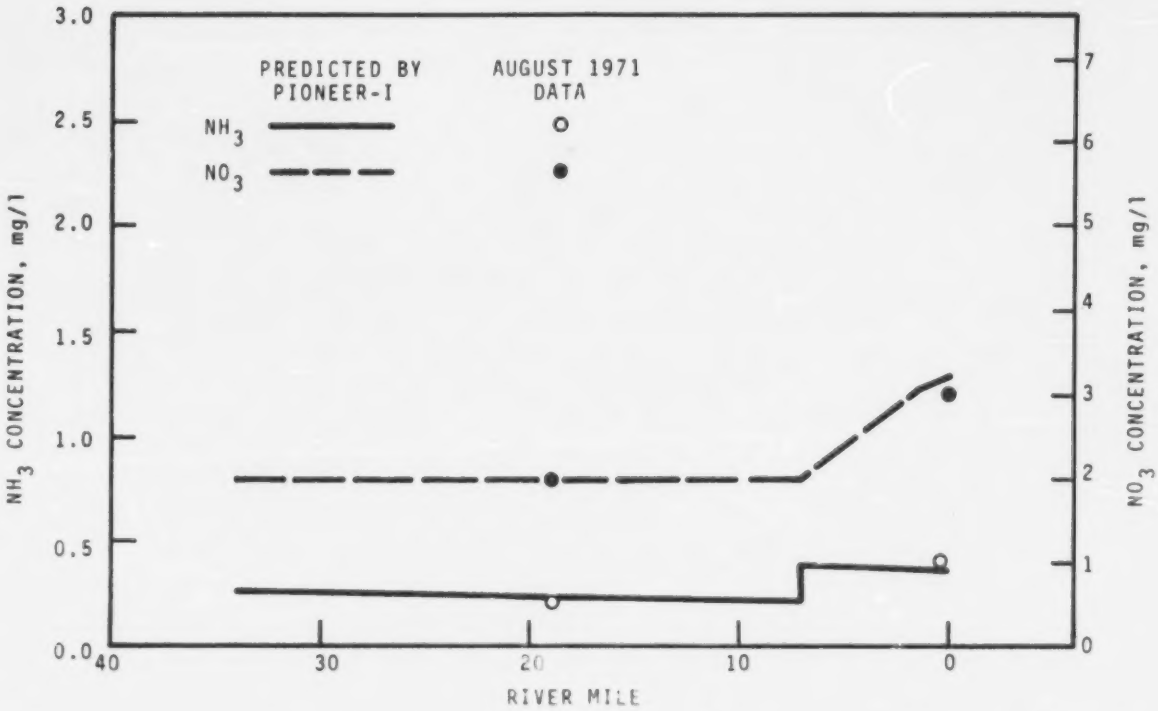


FIGURE 52. AMMONIA AND NITRATE PROFILES ON THE LITTLE THOMPSON RIVER FOR THE CALIBRATED PIONEER-I MODEL

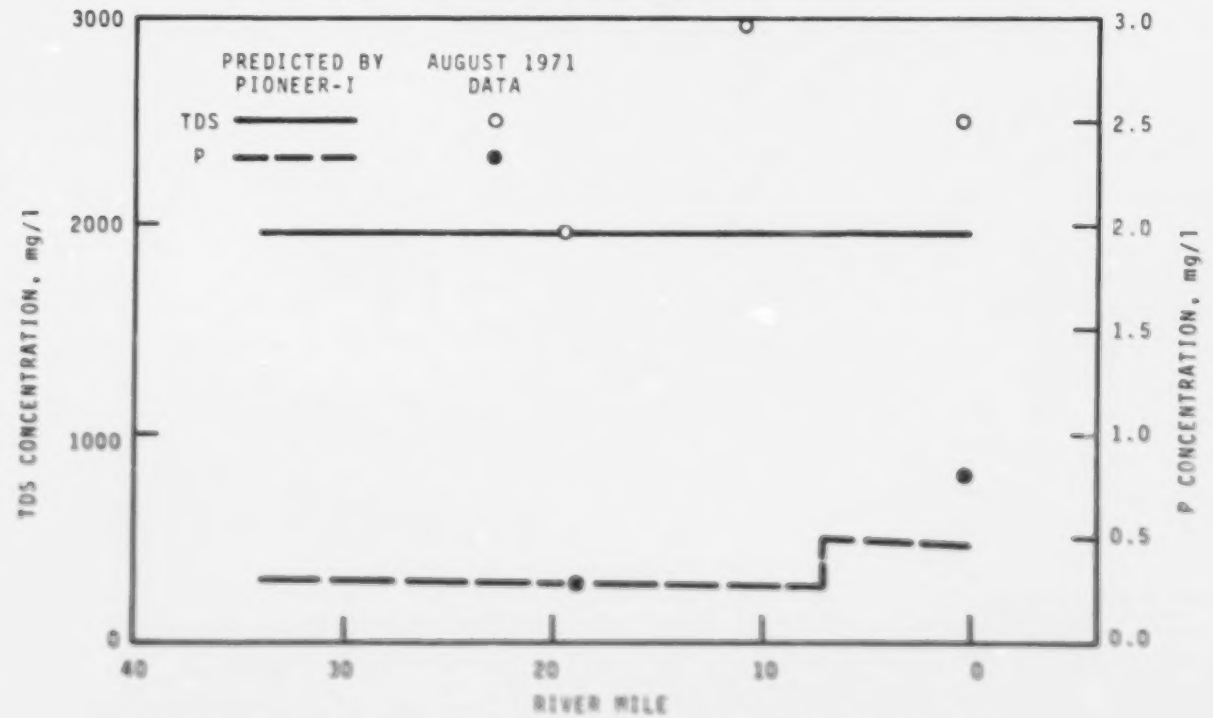


FIGURE 53. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON THE LITTLE THOMPSON RIVER FOR THE CALIBRATED PIONEER-I MODEL

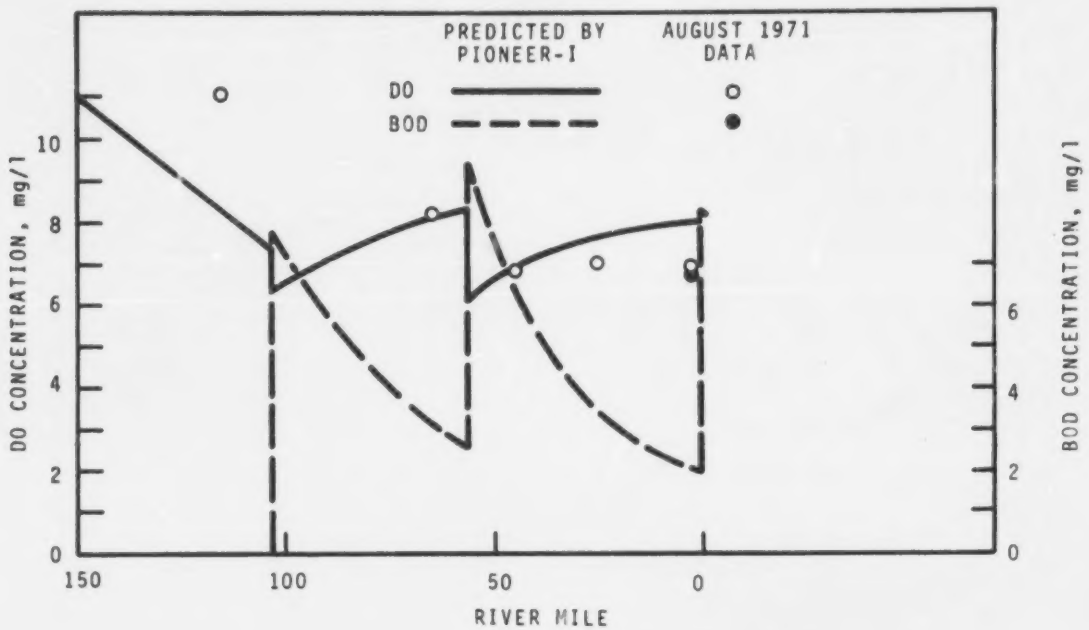


FIGURE 54. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON LODGEPOLE CREEK FOR THE CALIBRATED PIONEER-I MODEL

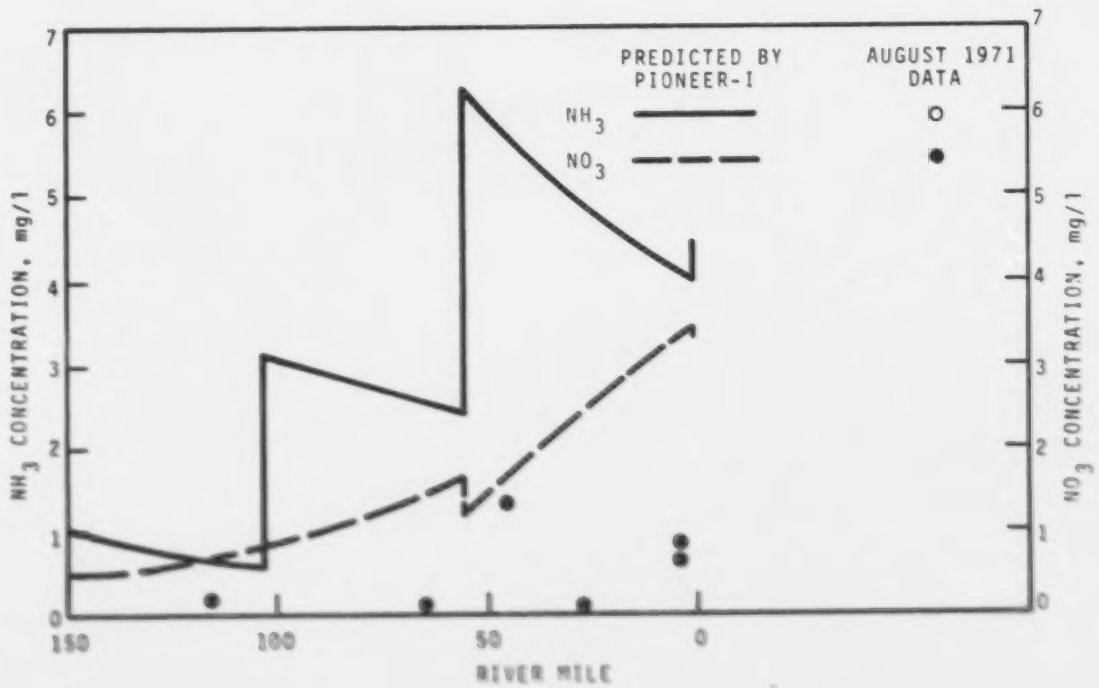


FIGURE 55. AMMONIA AND NITRATE PROFILES ON LODGEPOLE CREEK FOR THE CALIBRATED PIONEER-I MODEL

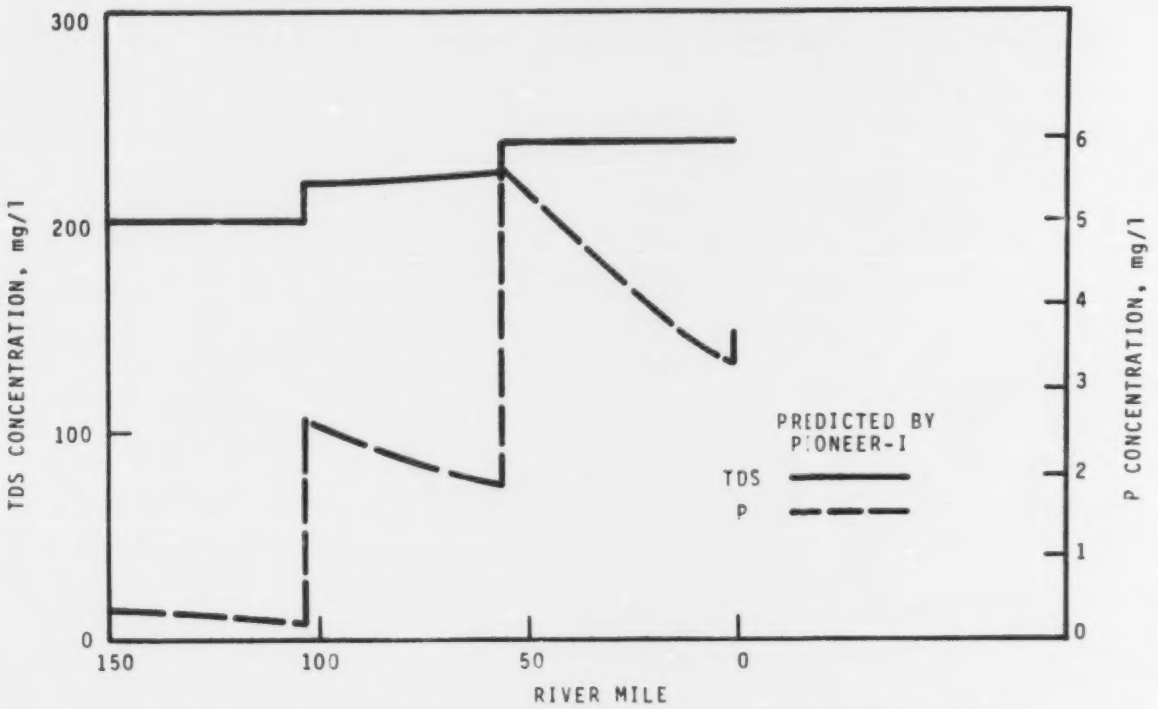


FIGURE 56. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON LODGEPOLE CREEK FOR THE CALIBRATED PIONEER-I MODEL

the River Basin. However, at the time the model was to be calibrated the average flows for the months of November and December 1971 were not available. Hence, flow data taken in December 1970 were used. In numerous cases the average flows were quite close to those actually measured and reported during the water quality survey in 1971, as shown for the Cache La Poudre and Big Thompson Rivers in Table 7. In other cases considerable differences exist as shown in Table 7, on the South Platte at Henderson and at Kersey. However, these same differences between the flows measured during the summer water quality survey and those calculated on a monthly average for August 1971 also existed. Hence, it is believed that the December 1970 flows were applicable for calibration purposes

TABLE 7

COMPARISON OF RIVER FLOW RATES,
AVERAGE DECEMBER 1970 AND SPOT MEASUREMENTS
DURING NOVEMBER-DECEMBER 1971

River	Location	Flow (cfs) Average Dec. 197	Measured Dec. 1971
Big Thompson	Coveland	30	18.2
Cache La Poudre	Greeley	166	132
South Platte	Henderson	492	208
South Platte	Kersey	1104	842

Flow Input Data

The flow data input for this calibration period are shown in Table 8. Also shown in the table are the computed inflows and withdrawals calculated between gaging stations using the detailed water balance outlined above. During the winter period very few water diversions were operating and relatively small amounts of inflows were computed, relative to the summer period, by water balance.

Water Quality Input Data

In general, all of the major effluent sources which existed during the summer period were also present during the winter period. The flow rates and effluent concentrations were assumed to be the same as for the summer period. The major difference was the presence of a number of sugar beet processing plants. The wastes from these plants normally have very high BOD concentrations, greater than 80 mg/ℓ. The actual strengths of the wastes from these plants were measured during the 1971 winter survey,[10] and these measured values were used in the model for calibration.

Instream water quality data were taken during the winter survey for only two parameters of interest, dissolved oxygen and biochemical oxygen demand. Therefore, no attempts were made to calibrate the other parameters, such as ammonia, nitrate, phosphorus or total dissolved solids in the model. Instead the rate of constants determined for the summer periods were used.

Calibration Results

The shapes of the DO and BOD profiles for most of the reaches in the River Basin which were not affected by sugar beet processing wastes were very similar to those calculated during the summer period. The DO levels were considerably higher due to two factors. First, the water temperatures were less than 4°C so that the DO saturation level was high (>10 mg/ℓ). Second, the BOD exertion rates were considerably reduced due to the low temperatures of the water.

The DO and BOD profiles for the South Platte River above river mile 200 are shown in Figure 57 along with the data measured during the 1971 winter survey. The predicted BOD values between river miles 290 and 312 are lower than those measured. This result would be expected since the average river flow rate used (from December 1970) in the calibration is considerably higher than that measured during the survey in 1971. A more detailed calibration was not attempted because of these differences in flows, however, the shapes

TABLE 8

AVERAGE FLOW CONDITIONS FOR SOUTH PLATTE RIVER BASIN MODEL CALIBRATION, DECEMBER 1970

ID* NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
SOUTH PLATTE RIVER				
33	Lake George Colo.	403.6	40.0	47.4
1	Below Cheeseman Lake, Colo.	374.5	87.4	
2	South Platte, Colo.	350.8	177.0	11.7
3	Waterton, Colo.	341.3	25.7	24.4
4	Littleton, Colo.	329.2	72.4	
5	Denver, Colo.	317.3	128.0	152.6
6	Henderson, Colo.	301.4	492.0	151.8
7	Kersey, Colo.	246.1	1104.0	
8	Weldona, Colo.	206.7	648.0	30.0
9	Balzac, Colo.	173.9	484.0	132.31
10	Julesburg, Colo.	86.6	618.0	
31	Paxton, Nebr.**	33.5		
32	North Platte, Nebr.	4.0	151.0	
NORTH FORK OF SOUTH PLATTE RIVER				
11	Grant, Colo.	39.0	29.1	49.3
12	South Platte, Colo.	0.3	78.4	

* The identification numbers correspond to those used in the system layout and data report.

** This station was discontinued.

ID NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
PLUM CREEK				
13	Plum Creek, Colo.	7.5	20.2	
BEAR CREEK				
14	Morrison, Colo.	10.8	21.8	16.8
15	Sheridan, Colo.	1.3	38.5	
CHERRY CREEK				
16	Cherry Creek, Colo.	32.1	2.8	
CLEAR CREEK				
17	Clear Creek, Colo.	45.1	41.0	
18	Golden, Colo.	17.5	80.3	12.5
19	Derby, Colo.	0.6	97.5	
ST. VRAIN CREEK				
20	Lyons, Colo.	34.3	16.7	54.2
24	Platteview, Colo.	1.3	201.0	
BOULDER CREEK				
21	Orodell, Colo.	28.8	56.0	
SOUTH BOULDER CREEK				
22	Eldorado Springs, Co	2.5	13.9	

ID NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
COAL CREEK				
23	Planview, Colo.	19.5	1.7	
BIG THOMPSON RIVER				
25	Drake, Colo.	37.6	29.9	
26	LaSalle, Colo.	1.6	81.7	
CACHE LA POUDRE RIVER				
27	Ft. Collins, Colo.	56.3	30.4	87.6
28	Greeley, Colo.	3.0	166.0	
LODGEPOLE CREEK				
29	Ralton, Nebr.	8.3	6.0	-4.3
30	Bushnell, Nebr.	114.0	5.2	

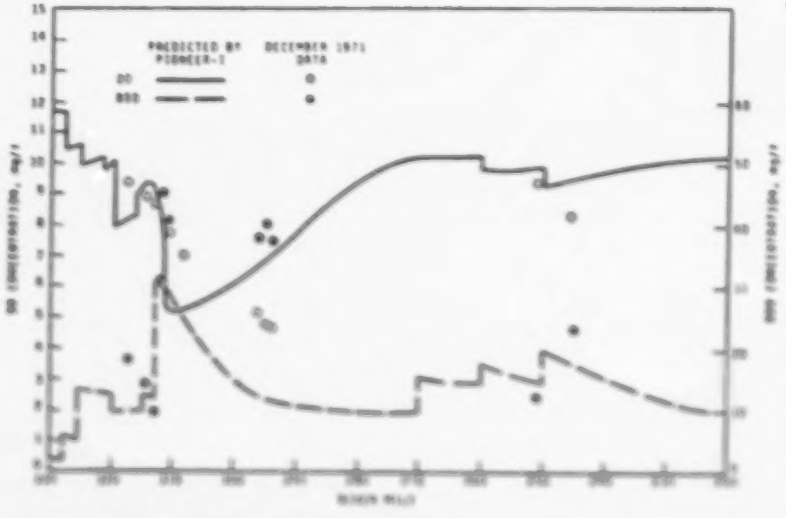


FIGURE 57. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON THE UPPER SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

of the predicted profiles indicate that the major sources have been included and the proper river dynamics accounted for.

The effects of the major sugar beet processing plants on the DO and BOD profiles are shown in Figures 58 and 59 for the lower South Platte and Cache La Poudre Rivers, respectively. The calibrated model predicts the profiles quite closely in both cases.

VERIFICATION OF THE PIONEER-I MODEL

In order to insure that the calibrated PIONEER-I model could predict DO and BOD profiles for conditions different from those used in calibration, a verification calculation was used. In choosing the period to use for verification two factors were considered. First, sufficient data should be available during the verification time period to permit a reasonable comparison of the predicted and measured results. Second, the time period selected should be reasonably close to the calibration period so that significant changes, such as the addition or elimination of major pollution sources, have not occurred. The period of August 1970 was chosen since it best met these criteria.

Flow Input Data

The flow data used in the verification calculations are shown in Table 9. Also given in this table are the inflows and withdrawals computed using the detailed water balance described above.

Water Quality Input Data

The same effluent flow rates and concentrations used in the calibration phase were also used in the verification. Each effluent source was checked to determine if it was in fact discharging during August 1970.

The instream water quality data used was taken by the Colorado State Health Department and retrieved from the EPA's STORET data system.

Verification Results

The profiles predicted for the August 1970 verification trial are shown in Figures 60-62 for the South Platte River. Reasonably good agreement is evident in these figures except in two cases. First, the ammonia nitrogen prediction is quite high. This result is not surprising since even with

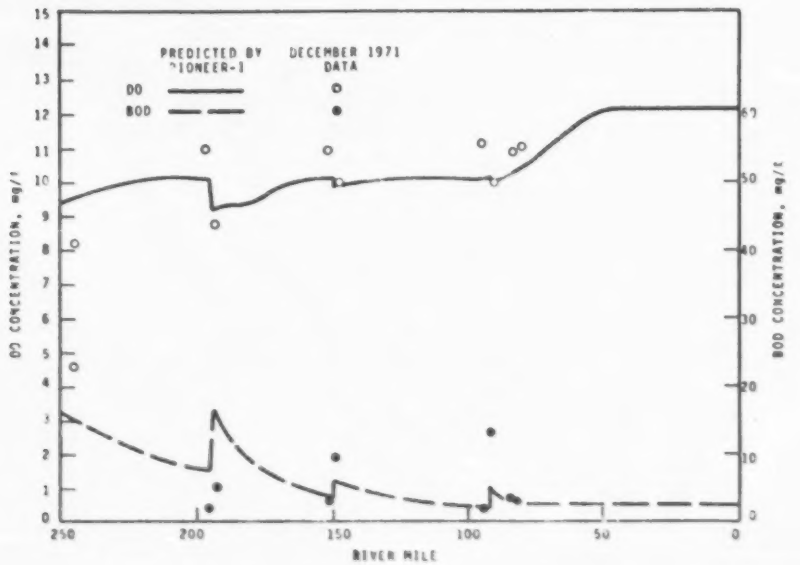


FIGURE 58. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND PROFILES ON THE LOWER SOUTH PLATTE RIVER FOR THE CALIBRATED PIONEER-I MODEL

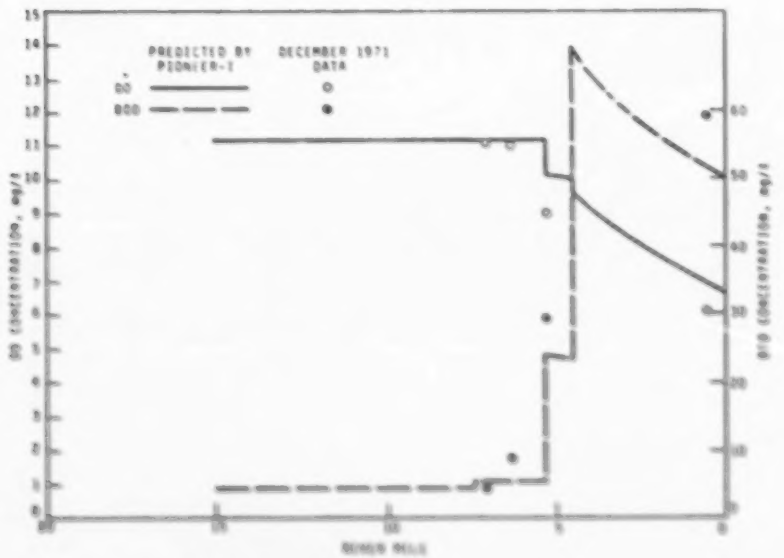


FIGURE 59. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND ON THE LOWER CACHE LA POUDRE RIVER FOR THE CALIBRATED PIONEER-I MODEL

TABLE 9

AVERAGE FLOW CONDITIONS FOR SOUTH PLATTE RIVER BASIN MODEL CALIBRATION, AUGUST 1970

ID* NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
SOUTH PLATTE RIVER				
33	Lake George Colo.	403.6	238.0	223.0
1	Below Cheeseman Lake, Colo.	374.5	461.0	
2	South Platte, Colo.	350.8	871.0	
3	Waterton, Colo.	341.3	376.0	
4	Littleton, Colo.	329.2	438.0	
5	Denver, Colo.	317.3	521.0	302.8
6	Henderson, Colo.	301.4	618.0	443.0
7	Kersey, Colo.	246.1	484.0	
8	Weldona, Colo.	206.7	384.0	216.8
9	Balzac, Colo.	173.9	348.0	420.5
10	Julesburg, Colo.	86.6	55.1	
31	Paxton, Nebr.	33.5	56.2	91.8
32	North Platte, Nebr.	4.0	148.0	
NORTH FORK OF SOUTH PLATTE RIVER				
11	Grant, Colo.	39.0	241.0	136.0
12	South Platte, Colo.	0.3	377.0	

* The identification numbers correspond to those used in the system layout and data report.

ID NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
PLUM CREEK				
13	Plum Creek, Colo.	7.5	4.6	
BEAR CREEK				
14	Morrison, Colo.	10.8	62.2	
15	Sheridan, Colo.	1.3	53.3	
CHERRY CREEK				
16	Cherry Creek, Colo.	32.1	2.1	
CLEAR CREEK				
17	Clear Creek, Colo.	45.1	178.0	
18	Golden, Colo.	17.5	220.0	68.8
19	Derby, Colo.	0.6	32.9	
ST. VRAIN CREEK				
20	Lyons, Colo.	34.3	106.0	383.6
24	Platteview, Colo.	1.3	225.0	
BOULDER CREEK				
21	Orodell, Colo.	28.8	84.9	20.6
SOUTH BOULDER CREEK				
22	Eldorado Springs, Co	2.5	30.6	

ID NO.	Gauge Location	River Mile	River Flow (cfs)	Computed Inflow or Withdrawal (cfs)
COAL CREEK				
23	Planview, Colo.	19.5	3.1	
BIG THOMPSON RIVER				
25	Drake, Colo.	37.6	96.7	
				300.0
26	LaSalle, Colo.	1.6	111.0	
CACHE LA POUDRE RIVER				
27	Ft. Collins, Colo.	56.3	280.0	
				531.3
28	Greeley, Colo.	3.0	64.3	
LODGEPOLE CREEK				
29	Ralton, Nebr.	8.3	3.9	
				-3.2
30	Bushnell, Nebr.	114.0	4.2	

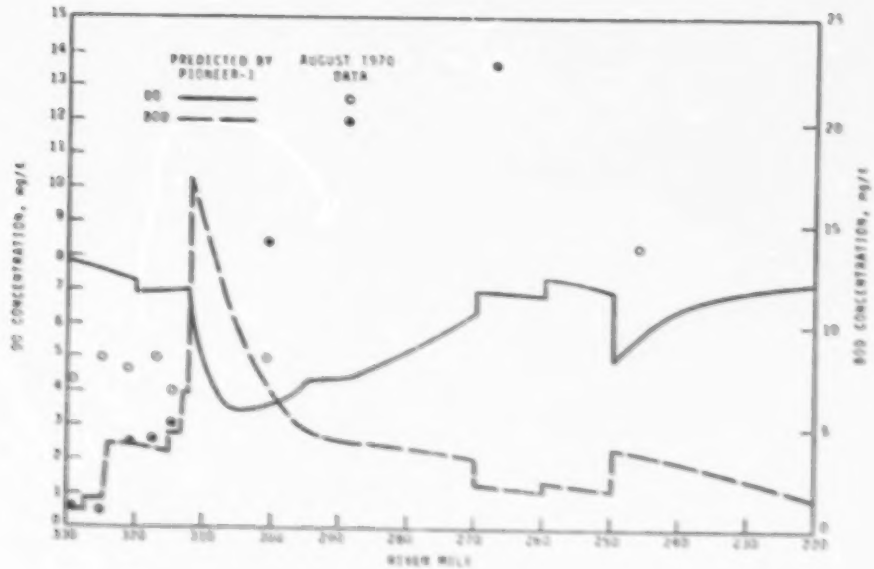


FIGURE 60. DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND ON THE SOUTH PLATTE RIVER FOR VERIFICATION OF THE PIONEER-I MODEL

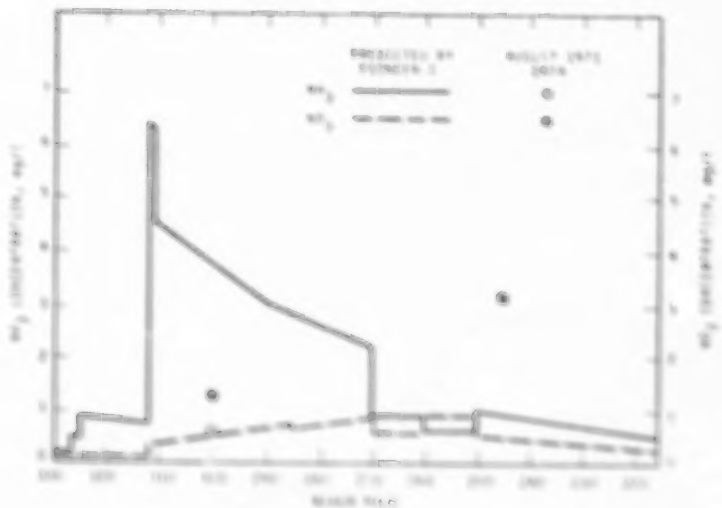


FIGURE 61. AMMONIA AND NITRATE PROFILES ON THE SOUTH PLATTE RIVER FOR VERIFICATION OF THE PIONEER-I MODEL

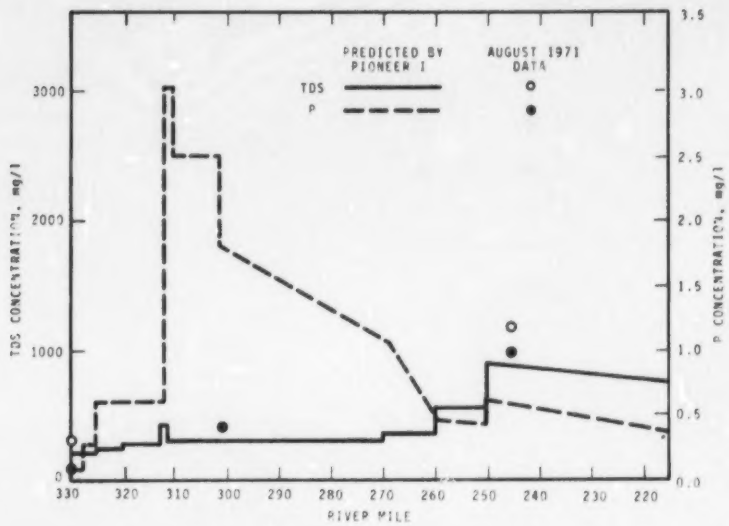


FIGURE 62. TOTAL DISSOLVED SOLIDS AND PHOSPHORUS PROFILES ON THE SOUTH PLATTE RIVER FOR VERIFICATION OF THE PIONEER-I MODEL

the calibrated model and the August 1971 data the ammonia predictions were extremely high. The second profile where agreement is poor is the dissolved oxygen levels above river mile 312. Measured values are less than 5 mg/ℓ while the predictions are greater than 7 mg/ℓ. This difference could be due to a number of things. For example, all of the measurements are taken quite early in the morning and the low DO may reflect considerable algal or benthic respiration. The low levels are surprising considering the corresponding low levels (<3 mg/ℓ) of BOD.

Very little data were available on the tributaries to the South Platte River. Table 10 presents the measured and predicted concentrations near the mouths of three of the major tributaries. In general, the agreement is quite good.

TABLE 10

VERIFICATION OF CALIBRATED PIONEER-I MODEL
ON TRIBUTARIES TO THE SOUTH PLATTE RIVER

River	Location	DO	BOD	NH_3	NO_3	TDS	P
		mg/l					
Cache La Poudre	Near Greeley						
Measured		5.8	13.0	1.40	1.70	1338	0.22
Predicted		6.0	15.0	1.50	0.17	1234	0.90
Big Thompson	Near Mouth						
Measured		6.3	4.8	0.4	2.5	1753	0.6
Predicted		7.6	3.3	0.4	1.0	913	0.46
Clear Creek	Near Mouth						
Measured		6.0	5.6	0.08	0.80	217	1.3
Predicted		6.9	3.5	0.62	0.76	402	0.84

SECTION VII

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SECTION VI

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